Integration of Global-Change Drivers and Biodiversity

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For my parents, for always being there for me.

For my family and friends, scattered all over the world.

Content

1. Abstract

We live in a changing world. People's actions have an impact in society as well as leaving a strong footprint on the environment, so much that we have come to name this era the *Anthropocene*. Data synthesis across disciplines can advance our understanding of how socio-ecological systems work and provide foundations to develop intervention programs to tackle the detrimental aspects of global change, such as loss of ecosystem services and biodiversity and reduced well-being. The aim of this doctoral thesis is to explore different ways of performing such integration, quantitatively (by determining the strength of effects) and qualitatively (through conceptualizations and literature reviews).

In the first chapter, I develop a conceptual framework on how people's understanding of *biodiversity* develops, linked to how the concept of *diversity* develops. Few studies have looked into the effects of early experiences, such as children's games, or otherwise everyday experiences, such as food-related activities, on how the understanding of the concept of biodiversity is formed. I synthesized opinions from a group of researchers from social and natural sciences, performed a literature review and developed a conceptualization of the learning of biodiversity stages. I suggest that everyday experiences could be relevant on how scientific misconceptions about biodiversity develop and call for further research in this direction.

In the second chapter, I report results from literature syntheses on the system of interactions between land-use change (e.g., for agriculture), biodiversity (species richness), productivity (biomass production) and human well-being (i.e. nutritional status). Land-use change, understood as the intensification of traditional activities or conversion of native landscapes to production, showed a large negative effect on biodiversity and moderate negative effects on productivity. Land-use change understood as interventions to increase both biodiversity and productivity (mostly starting gardens in semi-rural areas of least developed countries) showed a large positive effect on nutritional status (e.g., increasing vitamin profiles). Increasing plant species richness showed a large, positive effect on productivity. The overall network of effects constructed through these meta-analyses suggests feedbacks between variables that

are relevant to understanding how the system works holistically (e.g., why nutritional status does not always increase with interventions aimed at increasing productivity but not biodiversity). In the conclusions of this chapter, I suggest new working hypotheses for the specific interactions but also challenges encountered on data reporting and sharing.

In the third chapter, I used a system of variables that describes how competition for resources (nutrients and light), coupled with changes in biodiversity and biomass, determine the observed structure of plant communities. To synthesize the literature, I wrote down all hypotheses that have been tested about the direction and strength of the effects between these variables. Results showed that the five most tested hypotheses for this system were the least complex ones, and overall not the ones that were considered by conceptual and theoretical studies to be most representative for natural systems. With a conservative approach (i.e. without breaking down these hypotheses in their component pairwise interactions), these hypotheses were considered too different to be combined together in one quantitative analysis, yet none of these hypotheses has been independently tested often enough to support a robust statistical synthesis.

Overall, this thesis shows the high *value* but also the great *challenges* that we face when working interdisciplinary, across scales, and with multiple variables of complex socio-ecological systems. The *value* of this integration lies mainly in that it deals with that are more representative of how natural systems work. Integrative studies allow us to better understand the effects observed in nature and potentially could aid in tailoring our responses, in order to improve our human–nature relation and achieve sustainable development. The *challenges* include experimental design limitations, data reporting and data sharing issues, and lack of communication between working groups. These issues would need to be tackled within scientific communities as well as together with the rest of society, if we were to use research-synthesis tools such as meta-analysis in global-change sciences for reaching concrete ecosystem-management solutions.

Zusammenfassung

Wir leben in einer sich verändernden Welt. Unser Handeln wirkt sich auf die Gesellschaft aus und hinterlässt Spuren in der Umwelt. Deshalb wird diese Ära "das Anthropozän" genannt. Die disziplinübergreifende Datensynthese kann unser Verständnis der Funktionsweise von sozioökologischen Systemen verbessern. Sie kann auch Grundlagen für die Entwicklung von Programmen liefern, die die nachteiligen Aspekte des globalen Wandels abschwächen (z. B. Verlust der biologischen Vielfalt und vermindertes Wohlergehen). Das Ziel dieser Doktorarbeit ist es, verschiedene Wege zur Durchführung einer solchen Integration zu erforschen. Diese Integration kann quantitativ (durch Bestimmung der Stärke von Effekten) und qualitativ (durch Konzeptualisierungen und Literaturrecherchen) erfolgen.

Im ersten Kapitel habe ich einen konzeptionellen Rahmen dafür entwickelt, wie sich das Verständnis der Menschen für die biologische Vielfalt zusammen mit dem Konzept der Vielfalt entwickelt. Nur wenige Studien haben sich mit der Rolle früher Erfahrungen befasst (z. B. Kinderspiele oder Aktivitäten im Zusammenhang mit Lebensmitteln). Ich fasste die Meinungen einer Gruppe von Forschenden aus den Sozial- und Naturwissenschaften sowie aus einer Literaturrecherche zusammen. Damit entwickelte ich ein Konzept für Lernphasen der Biodiversität. Ich postuliere, dass alltägliche Erfahrungen relevant dafür sein könnten, wie sich wissenschaftliche Missverständnisse über die biologische Vielfalt entwickeln. Hierzu sollten weitere Forschungen durchgeführt werden.

Im zweiten Kapitel habe ich eine Literaturrecherche zu diesem sozioökoloigschen System von Wechselwirkungen durchgeführt: Landnutzungsänderungen (z. B. in der Landwirtschaft), Biodiversität (Artenreichtum), Produktivität (Biomasseproduktion) und Wohlbefinden der Menschen (d. H. Ernährungszustand). Landnutzungsänderungen, verstanden als die Intensivierung traditioneller Aktivitäten oder die Umstellung einheimischer Landschaften auf Produktion, wirkten sich stark negativ auf die biologische Vielfalt und mäßig negativ auf die Produktivität aus. Landnutzungsänderungen, die als Interventionen zur Steigerung der biologischen Vielfalt und Produktivität verstanden werden (hauptsächlich als Anpflanzung von Gärten in ländlich geprägten Gebieten der am wenigsten entwickelten Länder), zeigen einen stark

positiven Effekt auf den Ernährungszustand (z. B. Erhöhung der Vitaminprofile). Ein zunehmender Artenrecihtum von Pflanzen wirkte sich konsistent positiv auf die Produktivität aus. Die Ergebnisse dieser Studie legen nahe, dass es Rückkopplungen zwischen Variablen geben kann. In den Schlussfolgerungen dieses Kapitels schlage ich neue Arbeitshypothesen für die spezifischen Wechselwirkungen vor. Ich nenne auch die Herausforderungen bei der Datenberichterstattung.

Im dritten Kapitel beschäftigte ich mich mit dem Wettbewerb um Ressourcen (Nährstoffe und Licht), der zusammen mit Veränderungen der biologischen Vielfalt und der Biomasse die Struktur von Pflanzengemeinschaften bestimmt. Um die Literatur zusammenzufassen, habe ich alle Hypothesen aufgeschrieben, die für dieses System getestet wurden. Die Ergebnisse zeigen, dass die fünf an den häufigsten getesteten Hypothesen für dieses System die am wenigsten komplexen sind. Sie waren auch nicht diejenigen, die am meisten von theoretischen Studien für natürliche Systeme postuliert wurden. Bei einem konservativen Ansatz (ohne diese Hypothesen in ihre komponentenweise Wechselwirkung zu zerlegen) können verschiedene Hypothesen nicht in dieselbe quantitative Analyse einbezogen werden.

Insgesamt zeigt die vorliegende Arbeit den hohen Stellenwert, aber auch die großen Herausforderungen, denen wir uns stellen müssen, wenn wir interdisziplinär, maßstabsübergreifend und mit mehreren Variablen arbeiten. Der Wert dieser Integration besteht darin, dass Systeme mit diesen Merkmalen repräsentativer für die Natur sind. Integrative Studien ermöglichen es uns, sozioökologische Systeme besser zu verstehen und eine nachhaltige Entwicklung zu erreichen. Die Herausforderungen umfassen Probleme mit experimentellen Designs, unvollständige Datenberichte und mangelnde Kommunikation zwischen Arbeitsgruppen. Diese Fragen müssten sowohl innerhalb der Wissenschaftsgemeinschaften als auch gemeinsam mit der übrigen Gesellschaft angegangen werden. Dies wäre notwendig, um Forschungssynthesewerkzeuge wie die Metaanalyse in den Wissenschaften über den globalen Wandel zu verwenden sowi zur Erreichung konkreter Lösungen für das Management sozioökologischer Systeme

2. General Introduction

"Infinite diversity in infinite combinations…

symbolizing the elements that create truth and beauty."

(Spock-Nimoy, 1973)

2.1 Background

Think of an image that represents nature, to you. An image of a landscape, for example, that you would put next to a definition of *nature* in a dictionary. Perhaps an image of the beach or a tropical forest. Most likely that image includes living organisms, i.e. biodiversity, and a functioning ecosystem, i.e. energy and nutrient flows. In most of current landscapes, there would be another component: a sign of human presence, that can be in the form of land-use modification, contamination, species exploitation, or other human alterations of the environment. For terrestrial ecosystems, for example, only five percent of the land, mostly inaccessible and remote areas, remain undisturbed by human presence (Kennedy et al., 2019). We have modified our habitat so much, that the current time has been named by historians as *Anthropocene*, the time of humans (Lewis & Maslin, 2015). For the most part, environmental damage is unwanted; it is a collateral effect of development (Haigh & Griffiths, 2009), wars (Jarrett, 2003; Koppe, 2014), or ignorance of how natural systems work (Dovers et al., 1996). In some cases, we have the power to restore the environment; in other cases we must adapt to the new situation (Javeline, 2014). But in all cases, knowledge on how the systems work is useful, together with the will and means to act according to that knowledge. Knowing how natural systems work and which is the strength and direction in which we are modifying them can help us better define more accurate response interventions and predict future plausible scenarios of changes (Cornell et al., 2013).

Socio-ecological systems are networks of environmental, economic and social components (James et al., 2000). Considering interactions between these components in a holistic, systemic way is useful to study emerging properties of the system, such as fragility or resilience (Cretney, 2014; Petrosillo et al., 2006). Global change is a term used to describe the phenomena from anthropological and natural origins that modify the socio-ecological systems over time. Conceptualizing socio-ecological systems (i.e. using causal networks to show the direction in which components interact) has been the aim of numerous efforts in the last decades, in particular in the framework of global change, pushed also by activists and policy makers in governmental and non-governmental organizations (IPBES, 2019; MEA, 2005). This conceptualization could be, at times, a complex endeavor, given the number of components involved, direct and indirect impacts, and possible scales of analysis (Boons, 2013). But it is going one step further, from a concept to the quantification of effects, that provides the essential knowledge to develop and implement ecosystem management and interventions. For example, numerous in-depth studies on climate-change adaptation have advanced our idea on how ecosystems react under environmental change. Yet, without rigorous comparative quantitative analysis, there are too many uncertainties preventing us from using that knowledge to answer questions such as where and on what to direct climate investments (Biesbroek et al., 2017).

An interesting emergent property of systems is the *diversity* of its elements. What does “diversity” mean and why is it relevant to study it? According to its etymology, “diversity” comes from the Latin “divertere”, which means “turn aside” (synonym of avoid, deflect, deviate, diverge) (Oxford, 2019; Thesaurus, 2019). Perhaps this is why when we think of diversity, we often do so referring to the *differences* that enable us to separate things (people, species, objects), for example human diversity (Wood, 2003). Through my explorations of the term *diversity*, I came to define it as a property of a group of elements, that refers to the subjective degrees of similarities/differences between elements, along dimensions or aspects of interest. And in this thesis, I use this term to look for ways in which ideas can complement and converge, and for commonalities that would facilitate integration in socio-ecological systems.

Diversity has been found to be relevant in natural and social systems in order to maintain functionality of ecosystems, for resource management, evolution, adaptation and for governance (Becker & Ostrom, 1995; Leinster & Cobbold, 2011). This does not mean that *more* diversity should always be preferred or is needed for a system to work; it may also lead to chaos or inefficiency (Page, 2011). But it has been found across disciplines such as economy, physics, and ecology that a lack of diversity is often a negative attribute for sustainability as it reduces the robustness of complex systems against changes (Page, 2011). Hence the particular relevance of its study within global change sciences, was that the sustained function of systems over time is at stake.

Diversity is a recurrent topic throughout my thesis; in the first chapter I study the *diversity of understandings* of biodiversity, in the second one the *diversity of data* in complex socio-ecological systems and in the final chapter, the *diversity of hypotheses* about mechanisms that determine plant community structures. Furthermore, in all chapters biodiversity (short for *biological diversity* (Magurran, 2004)) is present as a relevant component. I am particularly interested in:

a) how people form an understanding of what biodiversity is,

b) how to use the diversity of studies available to determine the strength of effects in global change, and

c) how scientists produce and work with a diversity of hypotheses to advance knowledge in ecology.

a) Understanding Biodiversity

Current challenges in global change sciences are tightly linked to sustainable development (Reid et al., 2010). Climate change, land-use change/habitat loss, biodiversity loss, nutrient depletion, to name a few, will severely alter the way we use natural resources through ecosystem services. They are expected to have detrimental impacts on development goals already in the next generation and primarily in least developed regions (McKie, 2013; Mendelsohn et al., 2006). Reframing scientific problems as social problems can catalyse responses, as well as including citizens in scientific explorations (Bonney et al., 2015; Hackmann et al., 2014). But in order to do so, we must be able to communicate and translate scientific facts (Bracken et al., 2015). Untrained people may not necessarily see or understand the world in the same way as experienced or academically educated people do (Buijs, 2009).

There are multiple variables that influence our understanding of how the natural world works. It is in fact through early explorations of the world that we get first-hand knowledge of concepts like gravity, weather, or pain, and these experiences allow us to later associate complex concepts to them, through further experience and educational training (Johnston, 2005). Observational and experimental research in this direction is lacking, but the few studies available, for example, on perceptions of biodiversity, show that contexts such as background and nationality can affect the way in which we perceive levels of biodiversity (Campos et al., 2013; Lindemann-Matthies, 2017; Lindemann-Matthies et al., 2013).

b) Using data from diverse sources and disciplines for syntheses

Integration of data and ideas in socio-ecological systems requires crossing boundaries and working closely with people from other disciplines (Barry & Born, 2013). For example, human–fire interaction in tropical forest is one of these systems where an interdisciplinary approach is required. The natural (the biomes that are prone to fire) and the human component (the attitudes, practices and interests of land users/owners) of this system have usually been studied separately, often leading to misinterpretations of causes and mechanisms (Carmenta et al., 2011). Nevertheless, within-discipline studies are still important, as they advance knowledge on different aspects within a component; e.g., social, cultural, and economic aspects for social-sciences studies (Bowman et al., 2011) or climate, vegetation, and soil aspects for natural/earth sciences, and have the capacity to work at local scales or be detail-oriented (Dube, 2009). However, exploring coupled human and natural systems within fire–human interactions is what allowed researchers to do holistic conceptualizations, understand better the dynamics, feedbacks and subsystems, and develop more precise interventions (Spies et al., 2014).

c) Dealing with a diversity of hypotheses

Knowledge in academic settings evolves through the production and testing of logical hypotheses that intend to explain mechanisms, either from theoretical or observed systems (Black, 1946). The production of hypotheses is generally seen as a creative procedure, although there are authors that would use a methodological approach to develop them (Flick et al., 2000). Testing hypotheses leads to individual studies, papers, reports, and data that are produced massively around the world. Given this diversity of studies, research syntheses are required so as to uncover general patterns and identify knowledge gaps where more or different research is needed (Cooper & Hedges, 2009). There are a range of methods to connect individual sources of information (e.g., expert consultations, focus groups, meta-analysis, vote-counting), usually categorized as qualitative or quantitative based on the nature of their data and outcomes, being descriptive/textual in the first one and numeric in the later

(Koricheva et al., 2013; Pullin et al., 2016). The type of research synthesis needed depends on the question to be addressed, and generally it is recommended to use several methods, given that they complement each other, for a broader view on how a system works (Flick et al., 2000; Pullin et al., 2016; Pullin & Stewart, 2006).

2.2 Research justification

The Millennium Ecosystem Assessment (MEA) was a major global environmental assessment of the United Nations, performed in years 2000-2005 (MEA, 2005). One of its main goals was to link human actions with biogeochemical processes, to describe its relations and sources of change, and to inform policy, given the direct relevance to humanity's development. This assessment was followed by the International Panel on Climate Change and on Biodiversity and Ecosystem Services Panel and the Sustainable Development Goals (IPCC, IPBES, SDGs), which extended the focus to other species jeopardized by human action and put focus on the relevance of feedbacks between different human actions and ecosystem processes (CBD, 2018; IPBES, 2011, 2019).

These international programs have in common that they promote research synthesis and raise awareness of the need to work inter- and trans-disciplinary. It is in this framework in which my doctoral thesis was planned, as an exploration between interacting groups of variables in global change sciences, to advance knowledge in global-change systems. I performed this exploration at different scales (local, regional, global) and with different methods (descriptive, meta-analysis, interdisciplinary perspectives) in order to determine challenges and benefits of each. For the sake of reproducibility, quantitative analyses were the main target, when the available data would allow for them. To complement this effort, I also made use of semi-quantitative (e.g., vote counting), and descriptive methods, as well as discussions among experts. To my knowledge, there are currently no studies performing quantitative research synthesis between numerous variables from social, earth and natural sciences together, using published data from individual studies, despite the numerous policy frameworks that call for this type of integration and conceptual studies that have set a sound theoretical foundation (Bennett et al., 2015; Liu et al., 2015; Moon et al., 2014; Rudel, 2008; Steffen et al., 2015). Therefore, my efforts, although exploratory, are hopefully timely and useful to better understand global-change systems.

2.3 General aims

The overall aims of this thesis are to:

- Build conceptual networks of variables across disciplines involved in global change science
- Determine the strength of interactions between variables quantitatively and/or describe the dynamics of their relation qualitatively
- Determine at which scales it is possible to respond to international calls for data integration in global change sciences by using published data from individual studies through meta-analysis
- Inform the research community of particular outcomes of this integration, such as new working hypothesis that may be useful for further research
- Enumerate challenges to data integration and suggest ways to overcome them.

In each chapter of the thesis, I develop an integration of data or perspectives, using case studies represented in Figure 2.1 as networks of variables. Specific aims for each chapter are stated in Table 2.1.

Table 2.1: Questions and aims of the thesis per chapter

	Question addressed	Aim
Chapter 1: Improving our understanding of biodiversity through everyday experiences	How does the concept of biodiversity develop in people's minds?	Review available literature that has addressed this topic and summarize key ideas
		Develop a conceptual framework on how biodiversity understanding is formed
	What are the factors that affect our understanding of the concept of biodiversity?	Explore situations outside formal science education which may contribute to the forming of misconceptions on biodiversity
	What do researchers and lecturers from both social and natural sciences think about how people's understanding of biodiversity develops?	Integrate different perspectives from researchers working biodiversity in different discipline
Chapter 2: Systemic analysis of interactions between land use change, biodiversity, productivity, and nutrition	What is the strength of the interactions between multiple components of the global change system between land use change, biodiversity, productivity and nutritional status?	Perform one or more meta-analyses and reviews between components of a global change system
	Can this strength be quantified using published studies from diverse sources?	
	What are the advantages and challenges of performing systemic analyses with multiple components and inter-disciplinary?	Describe the type of outcomes that can be obtained through data integration
		Find challenges to data integration and develop possible recommendations
Chapter 3: Identification, comparison, and analysis of hypotheses in systematic review	What are the most tested hypotheses on competition for nutrition and light related to biodiversity and productivity in plant communities?	Find in the literature all tested hypotheses for this system
	What is the difference between them?	Look for commonalities, differences and group them by degree of compatibility
	Is it possible to find out which of the internal mechanisms of determination of the plant community structure is stronger?	Perform one or more meta-analyses with all available studies

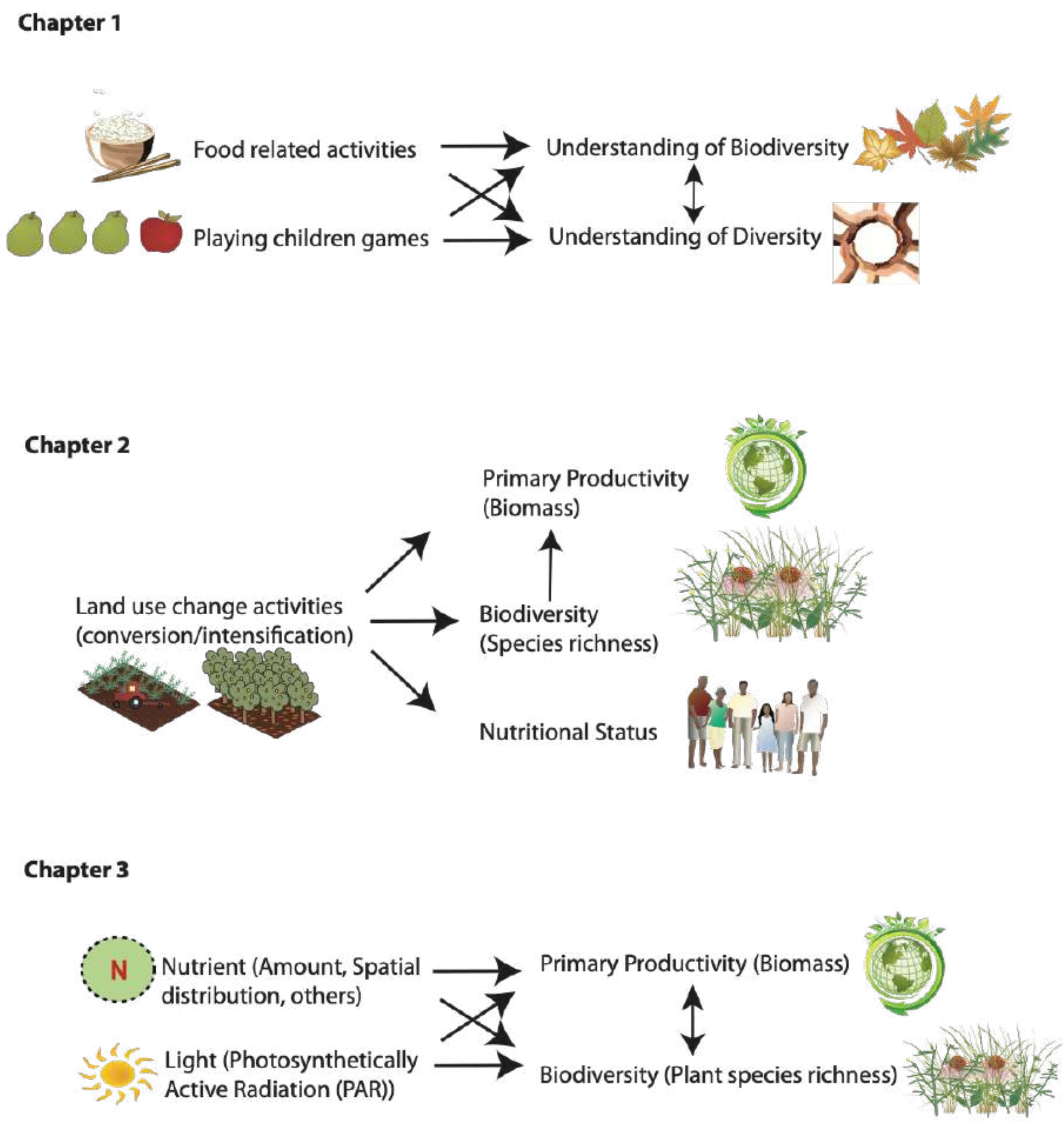

Fig. 2.1: Networks of variables per chapter

3. Chapter 1 – Improving our understanding of biodiversity through everyday experiences

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3.1 Abstract

How do people develop their understanding of the concept of biodiversity? Here we develop and present hypotheses about how the personal understanding of biodiversity is formed. We base our hypotheses on the theories of constructivism and conceptual change, from the field of education. We emphasize the potential relevance of extrinsic and circumstantial elements in shaping first a naïve, and then an expert understanding of biodiversity, and the relation between social and scientific understandings. We believe that our perspective facilitates the identification of sources of misconceptions, such as everyday experiences related to the concept of biodiversity.

We discuss in more detail two everyday experiences, namely certain games we play as children and food related experiences (e.g., gardening, cooking). Based on an examination of a type of children's game that often concerns biodiversity we hypothesize that the language used to describe the game and the activity itself creates negative connotations regarding biodiversity, allows little flexibility for dissent, and reduces recognition of variability among individuals. Secondly, we consider and discuss studies relating food activities with the construction of a biodiversity understanding. Food is one of the most intimate ways in which we interact with nature; we hypothesize that how and what people learn about food is relevant in the construction of a deep understanding of the properties of biodiversity.

Testing these hypotheses requires interdisciplinary research and will help prevent unintentional misrepresentation and misunderstanding of biodiversity, which could translate into greater alignment of people's perceptions of the value of nature.

Keywords: diversity, biodiversity attitudes, food experiences, children's games, environmental education

3.2 Introduction

Biodiversity is defined as the variety and number of living organisms in the world or in a particular habitat, including humans (CBD, 2010; Magurran, 2004). The scientific consensus is that biodiversity plays an important role in keeping ecosystems functioning and able to adapt to change (Cardinale et al., 2012; Duffy, 2009). Although the concept of biodiversity has increased exponentially in popularity over the past 30 years (Liu, Zhang, & Hong, 2011), there is also much evidence that humanity's collective actions continue to have negative consequences on it (Díaz et al., 2015; IPBES, 2019; McGrath, 2019). A review of conflicts in conservation sciences found that few biodiversity-human conflicts were related to lack of ecological information, compared to the greater number of conflicts related to the unwillingness of parties to engage, unrealistic goals, disparities between global and local interests, lack of financial capacity, sensationalist media representations, and legislation-related issues (Redpath et al., 2013). Misunderstandings about biodiversity can hinder progress on species conservation (Buijs, Fischer, Rink, & Young, 2008). In this context, we develop hypotheses concerning how people develop their understanding of the concept of biodiversity, and the role of everyday activities in shaping this understanding?

There are indications that our attitudes and actions towards biodiversity (and nature in general) are at least as dependent on the way we connect with it on a personal level as on the information derived from scientific research (Fischer & Young, 2007; Kellert & Wilson, 1993; Novacek, 2008; Schultz, 2002). We can identify biodiversity at a basic level with our bare senses because many aspects are easy to perceive through sounds, colours and shapes, an important asset for our survival (M. Oksanen & Pietarinen, 2004). It is then plausible that many experiences of diversity and biodiversity in our daily lives could be shaping the way we relate to it. A graphical representation of our understanding of the concept of diversity and further explanation on how we developed it can be found in the supplementary material (Fig. S1). The understanding of what is "more diverse" and why diversity may be valuable in a system, may differ for people according each person's background, interests, financial status, upbringing, education, experience and age, among other variables. These factors could be seen as "invisible membranes" that filter knowledge received (Roopnarine & Johnson, 2015).

From a philosophical point of view, biodiversity is a complex concept to grasp and has even been referred to as an optical illusion (Koricheva, Siipi, Oksanen, & Pietarinen, 2004). Furthermore, there are competing values that may influence our understanding of biodiversity, e.g., conservation of a particular population or variety, domesticated species, charismatic wild species and ecosystems that provide a higher number of services. *Biodiversity* from an anthropological perspective is a social construct in the same way *diversity* is a construct (Escobar, 2006; Meinard, Sylvain, & Bernhard, 2014; Qin, Muenjohn, & Chhetri, 2013). We propose the hypothesis that many experiences of daily life activities that require a handling of the concept of diversity and biodiversity, such as playing games or choosing and cooking our own food, are relevant to how people form attitudes towards and concepts around (bio)diversity even when they might have been underestimated.

The aim of this paper is to develop a perspective on how biodiversity understanding could be shaped by everyday experiences, to raise awareness of the current lack of research in this realm, and to present hypotheses that could promote dialogue and motivate research. With some specific examples, we propose research about ways to avoid accidentally causing misconceptions of (bio)diversity through these experiences. The perspective presented arose from interdisciplinary discussion between natural and social scientists, with expertise in biodiversity, global change, and education. We grounded our perspective in theories of constructivism and conceptual change from the field of education (Dahl & Killen, 2018; Duit & Treagust, 2003; Vosniadou, 2007). We, the authors are largely WEIRD (western, educated, industrialised, rich, democratic societies) (Henrich, Heine, & Norenzayan, 2010), and thus may have a narrower perspective that if we were more diverse.

3.3 How do people learn new concepts?

We explored the application of a constructivist approach in education (Piaget, 1953; Vosniadou, 2007; Vygotsky, 1978), to how the personal understanding of biodiversity is formed. In this learning theory, new knowledge is based on prior knowledge and is constructed through experiences and discoveries, according to their developmental stage (Piaget, 1953). Culture and language play an important role in how this process occurs and its outcome, through limiting the type of experiences that the learners are exposed to and through the impressions that the tutors imprint on the learning process (e.g., values, beliefs) (Vygotsky, 1978). From these ideas emerges a conceptual model of the formation of different personal understandings (Figure 3.1) and this creates multiple possible conceptions of human-nature relationships (Figure 3.2) (Chen, 2017; Meinard et al., 2014).

By conceptualizing how personal understanding of biodiversity is formed and how it relates to that of others, we aim to pave the path for future interdisciplinary research. This research could be oriented into identifying potential sources of misconceptions and contradictory messages, for example, when social norms promote homogeneity in human groups, while natural sciences education teaches biodiversity as an added value of a system. A possible approach to these studies could be looking for direct and indirect links between everyday experiences and biodiversity understanding. We present and discuss two examples: children games and food-related activities.

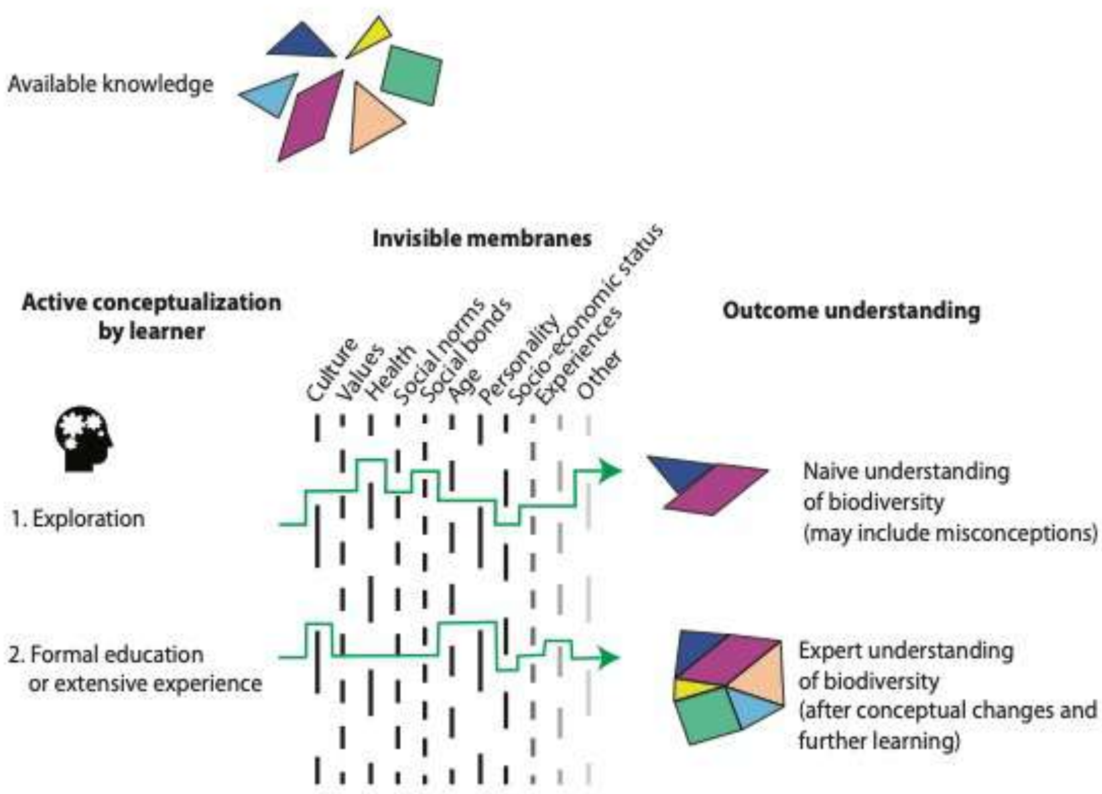

Fig. 3.1: A conceptual model of construction of the personal understanding of biodiversity.

In this model, knowledge is constructed actively by the learner putting together available pieces of information and going through “invisible membranes” that shape that construction. During the exploration phase, the learner forges a naïve understanding of a topic. When accessed, further education and experience allow the learner to correct possible misconceptions that may have occurred during the exploration phase (known as conceptual changes, i.e. note the position of the dark blue tile) and to go deeper into a topic, towards an expert understanding (i.e. adding more pieces of knowledge in the correct position to develop a bigger picture of a topic).

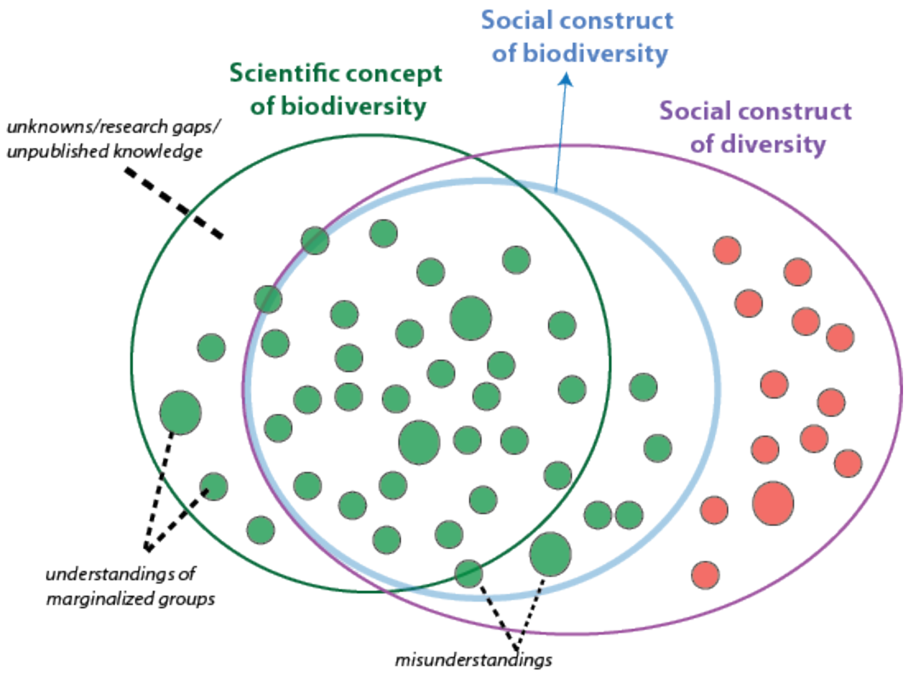

Fig. 3.2: **A conceptual model of relations between scientific (academic) and social constructs of biodiversity.** Green dots represent personal understandings of biodiversity; red dots represent personal understandings of diversity of elements (besides biological diversity). Understandings from experts are represented with bigger dots, and they can be within the green circle or outside (since those we consider to be experts, might not necessarily be correct). Understandings that are outside the green circle are "misunderstandings," which are concepts derived from social explorations that do not coincide with scientific theories.

3.4 Experiencing biodiversity through puzzles

Games and puzzles are one of the first ways in which we are introduced to many concepts in life (Brown & Freeman, 2001). Through playing and exploring, children instinctively build naïve explanations about how things work (based on experience, even without input from formal education). Games, puzzles, books and other media are informal sources of information that encourage interpretations about the biological world, consistent with the main beliefs of the mainstream culture (Geerdts, Van De Walle, & LoBue, 2016). Some of these "pre-scientific" conceptions stick with us despite formal education and are highly resistant to change (Duit & Treagust, 2003). For example, misunderstandings about natural selection, caused by over-simplification and interpretation of evolution as organisms' "anthropomorphic will to adapt" are widespread in initial education and hard to overcome even after lengthy higher education activities (Emmons, Lees, & Kelemen, 2018; Geerdts et al., 2016).

Children's picture books have been found to be relevant to how children understand the world around them, particularly regarding animals and plants (Ganea, Ma, & DeLoache, 2011; Kelemen, Emmons, Seston Schillaci, & Ganea, 2014). However, less research has been done on the impact of children's games and puzzles on this understanding. Naïve understandings and conceptual changes (Duit & Treagust, 2003) in sciences have been explored thoroughly for concepts in mathematics, physics and in biological concepts like evolution - but not for biodiversity (Thompson, 2006). We wonder whether such early experiences might have large and long-lasting effects on our naïve understandings of (bio)diversity, its components and importance.

One common children's puzzle, often known as "Which one does not belong?", encourages sorting of objects based on difference among them (Fig. 3.3).

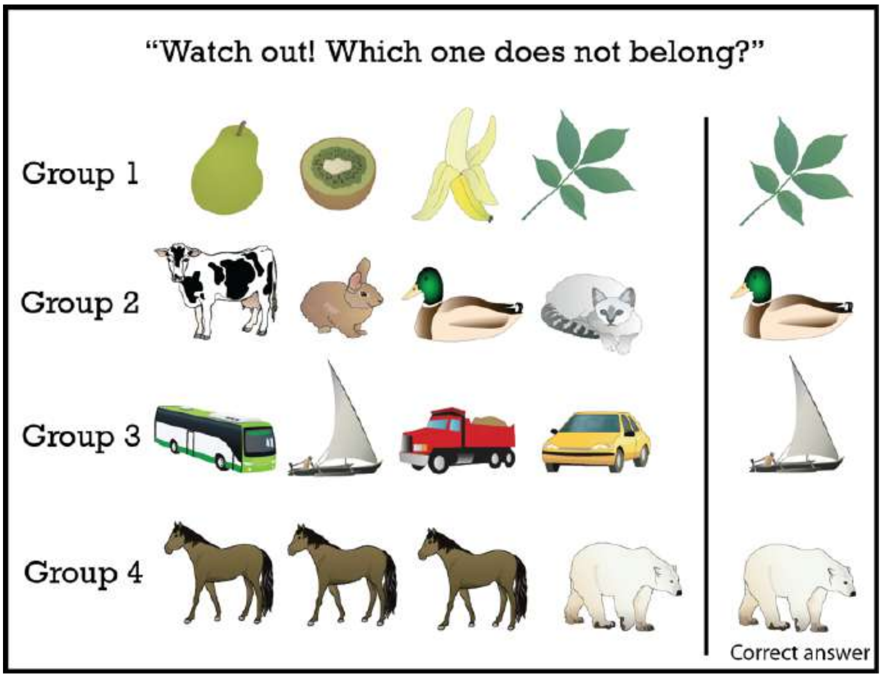

Fig. 3.3: A typical preschool sorting puzzle, with the title "Watch out! Which one does not belong" accurately representing common descriptions of what the puzzle concerns.

We examined this game in particular because the concept of diversity is clear (there is a group of objects that display some pattern of variation/difference in their properties) and because the player is required to identify something about and do something with that pattern of variation. Using Google Search, with the terms "Which does not belong?", we retrieved 102 puzzles from the first 300 images (after which the images became largely unrelated). We removed repeated images and ones with only text on them (Appendix 1). We looked into three aspects of these puzzles: 1) Language used, 2) Categorization of elements into groups assigned as “correct” (flexibility in dissent), 3) Homogenization of variability (level of differences between individuals categorized with the same name)

1) Language used in puzzles

The majority of the puzzles used language that implied difference is a undesirable property of an object – “Watch out! Which one does not belong”, “Cross out the picture that does not go with the rest”, “Select the one that does not fit”. We hypothesize that this could lead to a conceptual understanding that difference, and therefore diversity, in a group of objects is undesirable. We hypothesize that from the very earliest age the language of these puzzles creates the risk of development of a personal impression/understanding that being different is a negative attribute. This could be a misconception in general, and certainly is relative to understandings of the functional importance of biodiversity, in which biodiversity promotes ecosystem functioning and stability (Byrnes et al., 2014; Pennekamp et al., 2018). This is because being different can mean being complementary; things that fit and work together because they are different. What could be the title of these puzzles if they were aimed at creating an experience of differences more likely to result in a positive or neutral attitude towards them (e.g., which one is special/unique)? We hypothesise that simple changes in their titles and descriptions could fundamentally change players views of diversity and biodiversity.

2) Categorization into “correct” groups

An overwhelming majority of the puzzles only allowed one answer as “correct” (Table S1). Furthermore, the categories were made mostly based on structure or appearance of the elements, rather than function and advanced relations between elements (e.g., complementarities). One goal of sorting elements in these puzzles is that the student learns categories of elements that are standard in society. There is some level of usefulness in being able to distinguish these elements for practical reasons, but we were surprised to see little connection being established between elements and by the lack invitation to rethink groups towards different functions. One could wonder how subjective the decision is for one or another category. Furthermore, how hard is it later in life to advance from such simplified structures in order to understand a more complex world?

3) Reduced variation and lumping

The puzzles often exhibited little variability among objects of the same type; the most extreme case is similar to Group 4 in figure 1, when the same object is repeated several times with no differences between them. This is especially the case when the objects are organisms. For example, there are hundreds of types of pears (*Pyrus* sp.) known around the world (Bell, 1991). We hypothesise that this over-simplification of organisms could be partially responsible for limited appreciation of biodiversity, due to internal idealizations that homogeneity is normal and desirable. The implications of such idealizations could be many, from misunderstandings of the concept of biodiversity, to the loss of varieties and animals that we do not recognize as edible, "real" or "good". In science too, underestimating variability within groups, focusing on species levels and removing "outliers", has been the norm (Des Roches et al., 2018; Violle et al., 2012). More recently there is greater recognition and appreciation of the importance of differences among individuals of the same species as the basis of evolution, which derives an advantage by viewing diversity at a finer scale (Des Roches et al., 2018; Gugerli et al., 2008; Petchey & Gaston, 2002).

Many of these games also encourage lumping, by which we mean putting different objects into the same category. Scientists studying biodiversity tend to do a lot of lumping. However, it is becoming clearer that in many situations, lumping creates unjustified, and potentially dangerous perceptions. For example, a study of the potential effects of species extinctions on functional diversity concluded that "75% of the species could be lost before the disappearance of the first functional group" (Fonseca & Ganade, 2001). This percentage is arbitrary due to the subjectivity associated with assigning species to functional groups (Petchey & Gaston, 2002).

While lumping makes the world appear simpler and more understandable, it can have negative consequences such as being unwillingly subjected to biased classifications made by others (biased to a political view, for example), slowing progress (there is an inertia to change classifications that are established in a system) or limiting our creativity (Bowker & Leigh Star, 1999). The sense of safety from reducing the complexities comes with an unrealistic view of the world (Voinov, Seppelt, Reis, Nabel, & Shokravi, 2014). We hypothesize that research into this compression of diversity into categories/groups/tribes of seemingly identical objects will reveal that it is generally unnecessary and undesirable.

3.5 Experiencing biodiversity through food-related activities

A common and particularly intimate experience of biodiversity comes through what we put in our mouths. Eating is an important connection with nature, from which we obtain a diversity of nutrients for our existence. There are indications that children establish priorities in biodiversity conservation based on the type of biodiversity to which they are exposed (Ballouard, Brischoux, & Bonnet, 2011). We therefore hypothesise that analogies between cooking/eating and biodiversity theory could be used in education about biodiversity? Furthermore, we hypothesise that there is considerable potential to make more visible the biodiversity present in our diets. Given the wide variety of food across cultures, such tools could be at the same time useful to do further research in comparing how different societies make associations, possibly having an influence in the way they understand and build attitudes to biodiversity.

In Web of Science we searched using the terms: ("biodiversity" and "education" and ("eating" or "food")). We found 431 papers, from which we selected the ones in journals of social sciences (298), because they focused on the educational aspects and were relevant to well-being in relation to food-related activities, rather than to technical aspects of ecosystem management. We scanned through all titles, and found 69 that potentially analysed connections between understanding, education or learning of biodiversity and gardening, eating, agroecology and food-related activities. The content of their Abstracts the revealed 37 articles including study cases where the understanding of biodiversity (be it through experiences or in formal institutions) was linked to food-related practices (Appendix 3).

The 37 articles represent a rich corpus of research on the importance of dietary diversity (Kant, Schatzkin, Harris, Ziegler, & Block, 1993; Taruvinga, Muchenje, & Mushunje, 2013) and numerous studies that link biodiversity education and conservation to different aspects of nutrition (Chipeniuk, 1995; Crist, Mora, & Engelman, 2017; Fischer et al., 2019). Research shows that getting involved with the local plants and animals that sustain us has a positive influence in children's environmental attitudes and potentially helps them become better at making decisions regarding environmental management (Brewer, 2002). Even when those responses are not positive *per se* towards conservation, exposure to biodiversity helped students make wiser decision, for example, regarding toxic-nontoxic plants (Prokop & Fančovičová, 2019). We hypothesise that the activities we develop around food may be relevant to how our understanding of (bio)diversity is formed.

Gardening was singled as particularly relevant in relation to biodiversity conservation; this is well aligned with current global challenges in food security and agriculture (FAO, 2019). Agricultural diversity is increasingly recognised as a means for achieving global Sustainable Development Goals (Bioversity International, 2014). However, staple crops have largely displaced many traditional grains and even within them, the number of varieties of such crops in the global market is low (Bioversity International, 2014). Besides contributing to food security, growing our own food is beneficial for health and social bonding (Guitart, Pickering, & Byrne, 2014; Sempik, 2010), as well as being a practical class in biodiversity science. An exposure to a diversity of seeds, has been shown efficient in increasing the willingness of small household farmers to increase biodiversity in their yards (Snapp et al., 2019).

Education in sustainability and promoting community gardens are some ways of enhancing valuable experiences in this respect (e.g., family gardens "Schrebergarten" in Switzerland, Figure S3) (Millius, 2019). For example, including concepts of urban gardening and biodiverse foods in the school curriculum and menu, has shown to have the potential to bring positive results for children's performance at school (e.g., Biodiverse Edible Schools, in Berlin (Fischer et al., 2019); the School Food revolution, in UK, North America and Ghana (Morgan & Sonnino, 2008); Nature Club Programs, in China (Zhang, Zhao, & Chen, 2019)). Cultural traditions and socio-economically driven decisions affect the land use practices that directly modify landscape diversity, for example, in the man-made grasslands of Switzerland (Rudmann-Maurer, Weyand, Fischer, & Stöcklin, 2008) or the rice terraces of China (Wang, Zhang, Li, & Li, 2017). An interesting concept is that of Bio-Cultural Refugia, that highlights the connections between cultural practices, history of land management and biodiversity conservation (Barthel, Crumley, & Svedin, 2013). However, more research is needed on the relationship between cultural diversity of urban residents and the biodiversity in urban gardens, which remains largely unexplored (Botzat, Fischer, & Kowarik, 2016). Two possible directions for this research could be 1) developing analogies between cooking and biodiversity and 2) tracking diversity in our diets.

1) Cooking and biodiversity science analogies

Food fills our senses with a variety of colors, smells and textures; features derived from the intrinsic diversity of traits in the organisms we consume. Recipes are combinations of parts of different organisms that interact creating new elements of different value; a concrete analogy to the importance of species composition/combinations for phenomena such as ecological coexistence and stability (de Mazancourt et al., 2013; Michel Loreau & de Mazancourt, 2013). Because the food we make from recipes is more than the sum of its parts, putting a value on the contributions of each individual ingredient is difficult; this is analogous to the difficulties in isolating individual species contributions to ecosystem functioning (Lawton & Brown, 1994). For many recipes, diversity is a necessary requirement, but appropriate combinations and inclusion methods are also necessary; this is echoed in many biodiversity – ecosystem functioning experiments, in which diversity and composition are simultaneous important determinants of ecosystem functioning (de Mazancourt et al., 2013; M. Loreau, Naeem, & Inchausti, 2002; Spehn et al., 2005). Finally, more diverse ingredients do not necessarily make a better final dish, the same as more biodiversity is not, per se, always better, for example diversity of pathogens. We hypothesize that these parallelisms between food/cooking and biodiversity can be exploited in education about biodiversity to ensure appropriate and deep understanding of biodiversity.

2) Tracking biodiversity in diet

How can we better understand our experiences of diversity through food, and increase the visibility of local biodiversity? One option is to learn how to quantify the biodiversity in our diets and compare this through time and between people. We found in the literature no practical solutions to track the biodiversity in their diets that people could use regardless of their socio-economic status. We developed a table with the criteria that we consider relevant, so that it could be used independently or by educators, to strengthen people’s connection with the biodiversity in their everyday life (Fig. 3.4).

Complete the table with information about the food you had in the last week				
Food name (product)	*Beef*	*Corn*	*Cheese*	*Ginger*
Common name of organism	*Cow*	*Maize*	*Cow*	*Ginger*
Kingdom	*Animalia*	*Plantae*	*Animalia*	*Plantae*
Phylum/Division	*Chordata*	*Tracheophyta*	*Chordata*	*Tracheophyta*
Species (Latin name)	*Bos taurus*	*Zea mays*	*Bos taurus*	*Zingiber officinale*
Whole, part or derivated?	*part*	*part*	*derivate*	*part*
Name of part or part where it derivates from	*flesh*	*seed*	*milk*	*root*
Number of times consumed (e.g., per week)	*2*	*3*	*1*	*1*
Country where it comes from	*Switzerland*	*unknown*	*Switzerland*	*India*
Distance it travelled to your place (km)	*100*	----	*300*	*7000*

Fig. 3.4. **Example of a table that could help us analyse the biodiversity in our diets** (Biodiversity and Global Change MOOC, University of Zurich).

If we are not familiar with food diversity, it is possible that we will not understand how to protect its sources. In most of the developed world, the trend is for most people to be detached from the resources they consume; there are few environmental sustainability considerations when choosing their diets and there is a dietary delocalization, which is proven to be both environmentally damaging and unhealthy (Rose, Heller, & Roberto, 2019; van der Horst, Brunner, & Siegrist, 2011). Yet, it seems that many people yearn for contact with nature (Clark, Jones, & Reynolds, 2019). If we agree that food diversity is an important everyday experience shaping the understanding of (bio)diversity, then issues like food security and ensuring every person has access, not only to food, but to a variety of locally sourced food, becomes even more relevant. The diversity in the food we eat has implications beyond nutrition; it could shape the way we manage nature. We hypothesize that the lack of connection between the diversity in our diets and the natural world partially explains difficulties in understanding the concept of biodiversity?

3.6 A call for more research into how biodiversity understanding is shaped

In this article we have presented our perspective on how everyday experiences and practices could inadvertently shape personal understandings of biodiversity and provide numerous hypotheses that could be tested. We encourage people of all disciplines and backgrounds to do more research into the impact of everyday experiences on our understanding of (bio)diversity. For example, we proposed that during the development of educational children's games, the potential negative consequences on the understanding of (bio)diversity should be considered. The reasoning behind classifying and sorting games is the development of goal-oriented behaviors (executive functions), such as working memory or mental flexibility and learning-related cognitive skills, such as math or reading (Ackerman & Friedman-Krauss, 2017). We do not question the relevance of developing these skills, but we want to raise the hypothesis that such games may have unintended and potentially undesirable effects on how we understand (bio)diversity. It seems worth further exploring the effects that these games have on biodiversity understandings, for example by comparing such games with alternative ones that may include more appropriate connotations of diversity (e.g., Fig. S3). To understand the impact of games, collaborations between biodiversity scientists, education experts and games designers need to be developed and strengthened. Furthermore, we encourage more studies on the relationship between food experiences and people's understanding of biodiversity, as we believe they have great potential to sow the seeds for dialogue, as has been shown by Barthel et al. (2013) (Barthel et al., 2013).

It is important to note that we do not think that all experiences of biodiversity should be orchestrated to create only positive attitudes towards it. It is easy to find genuine experiences of biodiversity that lead to positive attitudes (e.g., aesthetic value of diverse pastures), or to negative attitudes (e.g., human wildlife conflicts for land resources) (Schnegg & Kiaka, 2018). However, align of people's understandings with the scientific conclusion that more often than not biodiversity loss has negative consequences for ecosystems will likely require that other sources of their understandings are accounting and cared for. Our values and perceptions can change and the great advances that we have made towards biodiversity conservation in the last years, mostly at local levels, illustrate this (Pickrell, 2006; "Success stories, Nature for all," 2019). We propose that these efforts should also be directed towards creating a more transparent, inclusive, and aligned social and scientific construct of biodiversity.

Declaration of interests

The authors declare no competing interests in the writing of this manuscript.

Author's contributions

M.A.P. performed the literature research, developed first draft of models, wrote first complete draft of manuscript and coordinated co-authors contributions. S.P. and M.C. participated in the development of the educational framework on personal and social understanding of biodiversity. F.A., N.B., A.D.-Z., K.H., P.N., M.M., M.J.S., M.S., B.S., V.W.M. and D.Z.-D. contributed to overall manuscript writing and provided references for specific sections and topics. I.R.G. participated in the development of the figures. O.L.P. initiated the idea of the manuscript, wrote initial summary and first draft of key sections of the manuscript, invited co-authors and supervised the development of manuscript.

3.7 References

Ackerman, D. J., & Friedman-Krauss, A. H. (2017). Preschoolers' Executive Function: Importance, Contributors, Research Needs and Assessment Options. *ETS Research Report Series*, *2017*(1), 1–24. https://doi.org/10.1002/ets2.12148

Ballouard, J.-M., Brischoux, F., & Bonnet, X. (2011). Children Prioritize Virtual Exotic Biodiversity over Local Biodiversity. *PLOS ONE*, *6*(8), e23152. https://doi.org/10.1371/journal.pone.0023152

Barthel, S., Crumley, C., & Svedin, U. (2013). Bio-cultural refugia—Safeguarding diversity of practices for food security and biodiversity. *Global Environmental Change*, *23*(5), 1142–1152. https://doi.org/10.1016/j.gloenvcha.2013.05.001

Bell, R. L. (1991). Pears (Pyrus). *Acta Horticulturae*, 657–700. https://doi.org/10.17660/ActaHortic.1991.290.15

Bioversity International. (2014). *Bioversity International's 10 year strategy 2014-2024. Agricultural biodiversity nourishes people and sustains the planet.* Retrieved from www.bioversityinternational.org

Botzat, A., Fischer, L. K., & Kowarik, I. (2016). Unexploited opportunities in understanding liveable and biodiverse cities. A review on urban biodiversity perception and valuation. *Global Environmental Change*, *39*, 220–233. https://doi.org/10.1016/j.gloenvcha.2016.04.008

Bowker, G. C., & Leigh Star, S. (1999). *Sorting things out: Classification and its consequences* (Geoffrey C. Bowker). Massachusetts Institute of Technology.

Brewer, C. (2002). Conservation Education Partnerships in Schoolyard Laboratories: A Call Back to Action. *Conservation Biology*, *16*(3), 577–579. Retrieved from JSTOR.

Brown, M. H., & Freeman, N. K. (2001). *We don't play that way at preschool*. *11*, 295–319.

Buijs, A. E., Fischer, A., Rink, D., & Young, J. C. (2008). Looking beyond superficial knowledge gaps: Understanding public representations of biodiversity. *International Journal of*

Biodiversity Science & Management, *4*(2), 65–80. https://doi.org/10.3843/Biodiv.4.2:1

Byrnes, J. E. K., Gamfeldt, L., Isbell, F., Lefcheck, J. S., Griffin, J. N., Hector, A., … Emmett Duffy, J. (2014). Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. *Methods in Ecology and Evolution*, *5*(2), 111–124. https://doi.org/10.1111/2041-210X.12143

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., … Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*(7401), 59–67. https://doi.org/10.1038/nature11148

CBD. (2010). Decision X/2. *Convention on Biological Diversity*. Presented at the The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets, Nagoya, Japan.

Chen, S. (2017). Global to Village| Toward Multiple Conceptions of Human-Nature Relationship: The “Human-Nature Unity” Frame Found in a Chinese Village. *International Journal of Communication; Vol 11 (2017)*. Retrieved from https://ijoc.org/index.php/ijoc/article/view/5474

Chipeniuk, R. (1995). Childhood Foraging as a Means of Acquiring Competent Human Cognition about Biodiversity. *Environment and Behavior*, *27*(4), 490–512. https://doi.org/10.1177/0013916595274003

Clark, D. N., Jones, D. N., & Reynolds, S. J. (2019). Exploring the motivations for garden bird feeding in south-east England. *Ecology and Society*, *24*(1). https://doi.org/10.5751/ES-10814-240126

Crist, E., Mora, C., & Engelman, R. (2017). The interaction of human population, food production, and biodiversity protection. *Science*, *356*(6335), 260. https://doi.org/10.1126/science.aal2011

Dahl, A., & Killen, M. (2018). A Developmental Perspective on the Origins of Morality in Infancy and Early Childhood. *Frontiers in Psychology*, *9*, 1736–1736. https://doi.org/10.3389/fpsyg.2018.01736

de Mazancourt, C., Isbell, F., Larocque, A., Berendse, F., De Luca, E., Grace, J. B., … Loreau, M. (2013). Predicting ecosystem stability from community composition and biodiversity. *Ecology Letters*, *16*(5), 617–625. https://doi.org/10.1111/ele.12088

Des Roches, S., Post, D. M., Turley, N. E., Bailey, J. K., Hendry, A. P., Kinnison, M. T., … Palkovacs, E. P. (2018). The ecological importance of intraspecific variation. *Nature Ecology & Evolution*, *2*(1), 57–64. https://doi.org/10.1038/s41559-017-0402-5

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., … others. (2015). The IPBES Conceptual Framework—Connecting nature and people. Retrieved from: Http://www.sciencedirect.com/science/article/pii/S187734351400116X. *Open Issue*, *14*, 1–16. https://doi.org/10.1016/j.cosust.2014.11.002

Duffy, J. E. (2009). Why biodiversity is important to the functioning of real-world ecosystems. *Frontiers in Ecology and the Environment*, *7*(8), 437–444. https://doi.org/10.1890/070195

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, *25*(6), 671–688. https://doi.org/10.1080/09500690305016

Emmons, N., Lees, K., & Kelemen, D. (2018). Young children's near and far transfer of the basic theory of natural selection: An analogical storybook intervention. *Journal of Research in Science Teaching*, *55*(3), 321–347. https://doi.org/10.1002/tea.21421

Escobar, A. (2006). Chapter 23: Does Biodiversity Exist? In *The Environment in Anthropology: A reader in Ecology, Culture and Sustainable Living* (Haenn, N. and Wilk, R. (eds.), pp. 243–245). U.S.A.: New York University Press.

FAO. (2019). *The State of the World's Biodiversity for Food and Agriculture* (J.Bélanger & D. Pilling (eds.)). Retrieved from http://www.fao.org/3/CA3129EN/ca3129en.pdf

Fischer, A., & Young, J. (2007). Understanding mental constructs of biodiversity: Implications for biodiversity management and conservation. *Biological Conservation*, *136*(2), 271–282. https://doi.org/10.1016/j.biocon.2006.11.024

Fischer, L., Brinkmeyer, D., Karle, S., Cremer, K., Huttner, E., Seebauer, M., … Kowarik, I. (2019). Biodiverse edible schools: Linking healthy food, school gardens and local urban biodiversity. *Urban Green Infrastructure – Connecting People and Nature for Sustainable Cities*, *40*, 35–43. https://doi.org/10.1016/j.ufug.2018.02.015

Fonseca, C. R., & Ganade, G. (2001). Species functional redundancy, random extinctions and the stability of ecosystems. *Journal of Ecology*, *89*(1), 118–125. https://doi.org/10.1046/j.1365-2745.2001.00528.x

Ganea, P. A., Ma, L., & DeLoache, J. S. (2011). Young Children's Learning and Transfer of Biological Information From Picture Books to Real Animals. *Child Development*, *82*(5), 1421–1433. https://doi.org/10.1111/j.1467-8624.2011.01612.x

Geerdts, M., Van De Walle, G., & LoBue, V. (2016). Using animals to teach children biology: Exploring the use of biological explanations in children's anthropomorphic storybooks. *Early Education and Development*, *27*(8), 1237–1249. https://doi.org/10.1080/10409289.2016.1174052

Gugerli, F., Englisch, T., Niklfeld, H., Tribsch, A., Mirek, Z., Ronikier, M., … Taberlet, P. (2008). Relationships among levels of biodiversity and the relevance of intraspecific diversity in conservation – a project synopsis. *Perspectives in Plant Ecology, Evolution and Systematics*, *10*(4), 259–281. https://doi.org/10.1016/j.ppees.2008.07.001

Guitart, D. A., Pickering, C. M., & Byrne, J. A. (2014). Color me healthy: Food diversity in school community gardens in two rapidly urbanising Australian cities. *Health & Place*, *26*, 110–117. https://doi.org/10.1016/j.healthplace.2013.12.014

Henrich, J., Heine, S. J., & Norenzayan, A. (2010). Most people are not WEIRD. *Nature*, *466*, 29.

IPBES. (2019). *Media Release: Nature's dangerous decline "unprecedented"; species extinction rates accelerating*. Retrieved from https://www.ipbes.net/news/Media-Release-Global-Assessment

Kant, A. K., Schatzkin, A., Harris, T. B., Ziegler, R. G., & Block, G. (1993). Dietary diversity and subsequent mortality in the First National Health and Nutrition Examination Survey Epidemiologic Follow-up Study. *The American Journal of Clinical Nutrition*, *57*(3), 434–440. https://doi.org/10.1093/ajcn/57.3.434

Kelemen, D., Emmons, N., Seston Schillaci, R., & Ganea, P. A. (2014). *Young children can be taught basic natural selection using a picture-storybook intervention*. *25*(4), 893–902. https://doi.org/10.1177/0956797613516009

Kellert, S., & Wilson, E. (1993). Chapter 2: The biological basis for human values of nature. In *The Biophilia Hypothesis*. Island Press, Washington, DC.

Koricheva, J., Siipi, H., Oksanen, M., & Pietarinen, J. (2004). The phenomenon of biodiversity. In Markku Oksanen & J. Pietarinen (Eds.), *Philosophy and Biodiversity*. Cambridge University Press.

Lawton, J. H., & Brown, V. K. (1994). Redundancy in Ecosystems. In E.-D. Schulze & H. A. Mooney (Eds.), *Biodiversity and Ecosystem Function* (pp. 255–270). https://doi.org/10.1007/978-3-642-58001-7_12

Liu, X., Zhang, L., & Hong, S. (2011). Global biodiversity research during 1900–2009: A bibliometric analysis. *Biodiversity and Conservation*, *20*(4), 807–826. https://doi.org/10.1007/s10531-010-9981-z

Loreau, M., Naeem, S., & Inchausti, P. (2002). *Biodiversity and Ecosystem Functioning: Synthesis and Perspectives*. New York: Oxford Univ. Press.

Loreau, Michel, & de Mazancourt, C. (2013). Biodiversity and ecosystem stability: A synthesis of underlying mechanisms. *Ecology Letters*, *16*(s1), 106–115. https://doi.org/10.1111/ele.12073

Magurran, A. (2004). *Measuring Biological Diversity*. UK: Blackwell Publishing.

McGrath, M. (2019, June 5). Nature crisis: Humans threaten 1 m species with extiction. *BBC*. Retrieved from https://www.bbc.com/news/science-environment-48169783

Meinard, Y., Sylvain, C., & Bernhard, S. (2014). A Constructivist Approach Toward a General Definition of Biodiversity. *Ethics, Policy & Environment*, *17*(1), 88–104. https://doi.org/10.1080/21550085.2014.885490

Millius, S. (2019). Familiengärten sind die grünen Lungen einer Stadt. *Die Ostschweiz*. Retrieved from https://www.dieostschweiz.ch/artikel/familiengaerten-sind-die-gruenen-lungen-einer-stadt-a3ydn6J

Morgan, K., & Sonnino, R. (2008). *The school food revolution* (1st edition). London: Earthscan, from Routledge.

Novacek, M. J. (2008). Engaging the public in biodiversity issues. *Proceedings of the National Academy of Sciences*, *105*(Supplement 1), 11571. https://doi.org/10.1073/pnas.0802599105

Oksanen, M., & Pietarinen, J. (2004). *Philosophy and Biodiversity*. U.S.A.: Cambridge University Press.

Pennekamp, F., Pontarp, M., Tabi, A., Altermatt, F., Alther, R., Choffat, Y., … Petchey, O. L. (2018). Biodiversity increases and decreases ecosystem stability. *Nature*, *563*(7729), 109–112. https://doi.org/10.1038/s41586-018-0627-8

Petchey, O. L., & Gaston, K. J. (2002). Functional diversity (FD), species richness and community composition. *Ecology Letters*, *5*(3), 402–411. https://doi.org/10.1046/j.1461-0248.2002.00339.x

Piaget, J. (1953). *The origin of intelligence in the child* (Routledge and Kegan Paul). London.

Pickrell, J. (2006). Top 10: Conservation successes and failures. *New Scientist*. Retrieved from https://www.newscientist.com/article/dn9963-top-10-conservation-successes-and-failures/

Prokop, P., & Fančovičová, J. (2019). The perception of toxic and non-toxic plants by children and adolescents with regard to gender: Implications for teaching botany. *Journal of Biological Education*, *53*(4), 463–473. https://doi.org/10.1080/00219266.2018.1501405

Qin, J., Muenjohn, N., & Chhetri, P. (2013). A Review of Diversity Conceptualizations: Variety, Trends, and a Framework. *Human Resource Development Review*, *13*(2), 133–157. https://doi.org/10.1177/1534484313492329

Redpath, S. M., Young, J., Evely, A., Adams, W. M., Sutherland, W. J., Whitehouse, A., … Gutiérrez, R. J. (2013). Understanding and managing conservation conflicts. *Trends in Ecology & Evolution*, *28*(2), 100–109. https://doi.org/10.1016/j.tree.2012.08.021

Roopnarine, L., & Johnson, J. E. (2015). *Play and diverse cultures: Implications for early childhood education*. 295–319. https://doi.org/10.1016/S0270-4021(01)80012-4

Rose, D., Heller, M. C., & Roberto, C. A. (2019). Position of the Society for Nutrition Education and Behavior: The Importance of Including Environmental Sustainability in Dietary Guidance. *Journal of Nutrition Education and Behavior*, *51*(1), 3-15.e1. https://doi.org/10.1016/j.jneb.2018.07.006

Rudmann-Maurer, K., Weyand, A., Fischer, M., & Stöcklin, J. (2008). The role of landuse and natural determinants for grassland vegetation composition in the Swiss Alps. *Basic and Applied Ecology*, *9*(5), 494–503. https://doi.org/10.1016/j.baae.2007.08.005

Schnegg, M., & Kiaka, R. D. (2018). Subsidized elephants: Community-based resource governance and environmental (in)justice in Namibia. *Geoforum*, *93*, 105–115. https://doi.org/10.1016/j.geoforum.2018.05.010

Schultz, P. W. (2002). Inclusion with Nature: The Psychology of Human-Nature Relations. In *Psychology of Sustainable Development* (Schmuck P., Schultz W.P. (eds)). Boston, MA: Springer.

Sempik, J. (2010). Green care and mental health: Gardening and farming as health and social care. *Mental Health and Social Inclusion*, *14*(3), 15–22. https://doi.org/10.5042/mhsi.2010.0440

Snapp, S., Bezner Kerr, R., Ota, V., Kane, D., Shumba, L., & Dakishoni, L. (2019). Unpacking a crop diversity hotspot: Farmer practice and preferences in Northern Malawi.

International Journal of Agricultural Sustainability, *17*(2), 172–188. https://doi.org/10.1080/14735903.2019.1591657

Spehn, E. M., Hector, A., Joshi, J., Scherer-Lorenzen, M., Schmid, B., Bazeley-White, E., … Lawton, J. H. (2005). Ecosystem effects of biodiversity manipulations in european grasslands. *Ecological Monographs*, *75*(1), 37–63. Retrieved from Scopus.

Success stories, Nature for all. (2019). Retrieved from IUCN website: http://natureforall.global/success-stories-home

Taruvinga, A., Muchenje, M. V., & Mushunje, A. (2013). *Determinants of rural household dietary diversity: The case of Amatole and Nyandeni districts, South Africa*. *2*(4), 2233–2247.

Thompson, F. (2006). An exploration of common student misconceptions in science. *International Education Journal*, *7*(4), 553–559.

van der Horst, K., Brunner, T. A., & Siegrist, M. (2011). Ready-meal consumption: Associations with weight status and cooking skills. *Public Health Nutrition*, *14*(2), 239–245. https://doi.org/10.1017/S1368980010002624

Violle, C., Enquist, B. J., McGill, B. J., Jiang, L., Albert, C. H., Hulshof, C., … Messier, J. (2012). The return of the variance: Intraspecific variability in community ecology. *Trends in Ecology & Evolution*, *27*(4), 244–252. https://doi.org/10.1016/j.tree.2011.11.014

Voinov, A., Seppelt, R., Reis, S., Nabel, J. E. M. S., & Shokravi, S. (2014). Values in socio-environmental modelling: Persuasion for action or excuse for inaction. *Environmental Modelling & Software*, *53*, 207–212. https://doi.org/10.1016/j.envsoft.2013.12.005

Vosniadou, S. (2007). Conceptual Change and Education. *Human Development*, *50*(1), 47–54. https://doi.org/10.1159/000097684

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Wang, T., Zhang, Z., Li, Z., & Li, P. (2017). Grazing management affects plant diversity and soil properties in a temperate steppe in northern China. *Catena*, *158*, 141–147. https://doi.org/10.1016/j.catena.2017.06.020

Zhang, W., Zhao, J., & Chen, J. (2019). Nature club programs promote adolescents’ conservation behavior: A case study in China’s biodiversity hotspot. *The Journal of Environmental Education*, *50*(3), 192–207. https://doi.org/10.1080/00958964.2019.160448

3.8 Supplementary material

Appendix 1: Tables

Table S3.1: Information on the images retrieved from google search using the terms "Which does not belong?". Each image is one column and the numbers in the cells correspond to the number of puzzles per image (e.g., I1: Image 1).

Topic	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20
Food or drink		2							1			1	1							
Non-food animals and plants		3									1	1				2				
Elements of common use			1							2	3	2				1		1	1	
Geometric figures				6	1	1								6	4					
Numbers							1	1									1			1
Mixed	4									2						1		3		
Other		1										1								
Classification based on:																				
Structure or appearance based		3		6	1				1	2		2	1	6	4				1	1
Applied function of element	3	2	1							2	4	3				4		4		
Advanced relations between objects	1	1				1	1	1									1			
Number of answers allowed																				
One answer correct	4	6	1	6	1		1		1	4	3	5	1	6	4	4	1	4	1	1
More than one answer correct						1		1			1									

…continues…**Topic**	**I21 (1)**	**I22**	**I23**	**I24**	**I25**	**I26**	**I27**	**I28**	**I29**	**I30**	**I31**	**I32**	**I33 (text)**	**I34**	**I35 (22)**	**I36**	**I37**	**I38 (text)**	**I39**	**I40**
Food or drink	NA			1	1								NA		NA					
Non-food animals and plants	NA	1					1						NA		NA					
Elements of common use	NA									1	1	2	NA	2	NA					
Geometric figures	NA					1							NA		NA					
Numbers	NA							1	2				NA		NA		4	1	1	
Mixed	NA		4								4	2	NA		NA	3				
Other	NA												NA		NA					1
Classification based on:																				
Structure or appearance based	NA	1		1	1	1	1		2	1	5		NA		NA	1				
Applied function of element	NA		4									4	NA	2	NA	1				
Advanced relations between objects	NA							1					NA		NA	1	4	1	1	1
Number of answers allowed																				
One answer correct	NA	1	4	1	1	1	1		2	1	5	4	NA	2	NA			1	1	1
More than one answer correct	NA							1					NA		NA	3	4			

…continues…**Topic**	**I41 (broken)**	**I42**	**I43**	**I44**	**I45**	**I46**	**(37)**	**I47**	**I48 (text)**	**I49**	**I50**	**Total**
Food or drink	NA	1			4	NA			NA			**12**
Non-food animals and plants	NA					NA			NA	1		**10**
Elements of common use	NA					NA			NA			**17**
Geometric figures	NA					NA			NA			**19**
Numbers	NA					NA		3	NA			**16**
Mixed	NA					NA			NA			**23**
Other	NA		1	1		NA			NA		1	**5**
Classification based on:												**Total**
Structure or appearance based	NA	1			3	NA			NA	1		**47**
Applied function of element	NA			1	1	NA			NA			**36**
Advanced relations between objects	NA		1			NA		3	NA		1	**19**
Number of answers allowed												**Total**
One answer correct	NA	1	1	1	4	NA		3	NA	1	1	**91**
More than one answer correct	NA					NA			NA			**11**

Appendix 2: Figures

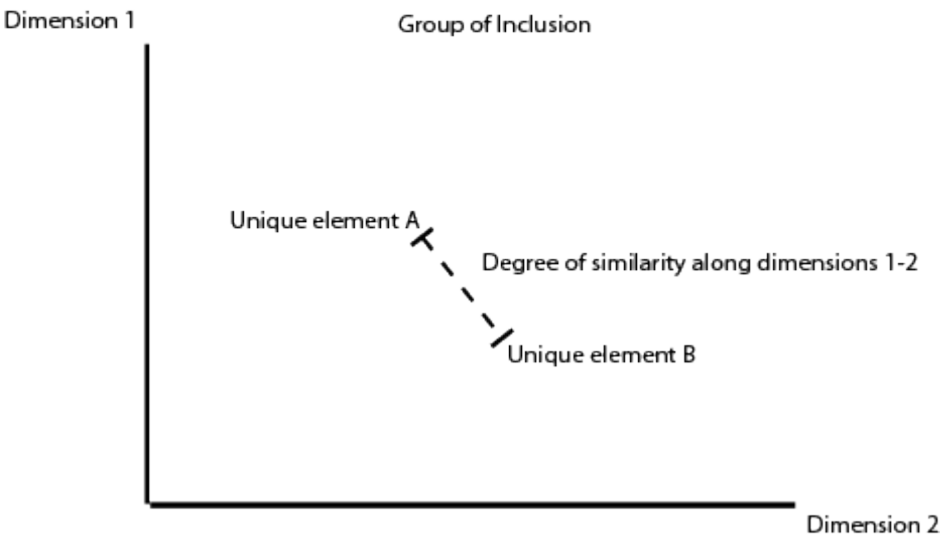

Fig. S3.1: Graphical representation of the concept of diversity. The distance between unique elements within a group of inclusion is defined by the degree of similarity along several dimensions, arbitrarily used to characterize them

We use the following two points to conceptualize diversity:

- understanding diversity implies understanding the unique aspects of elements, as much as the aspects shared with other elements (their degree of similarity), and
- the concept of diversity is tightly linked with the concept of inclusion since we can only define a group of elements as diverse, when they are all part of that group.

The degree of similarity between elements of a group depends on the type and number of dimensions in which we choose to describe it. Hence, characterizations of diversity will always show a reduced picture of the whole true diversity in the group. Which dimensions we choose should be done by agreement between all interested parties in describing this diversity, with an instrumental aim of doing so and the knowledge that it does not depict the entire diversity of the group. The number and type of dimensions, the size of the group of inclusion, as well as the position within the space of the elements based on their unique characteristics is for most systems in the world arguable, subjective and can change over time.

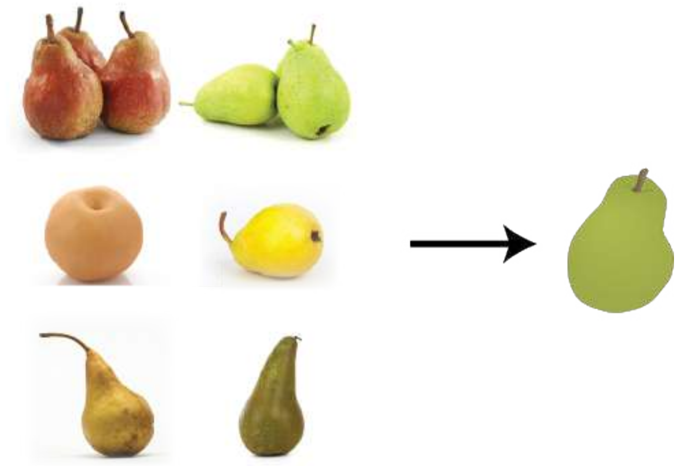

Fig. S3.2: Example of how pears of different varieties, compared to the widespread representation of a pear in children's books and games.

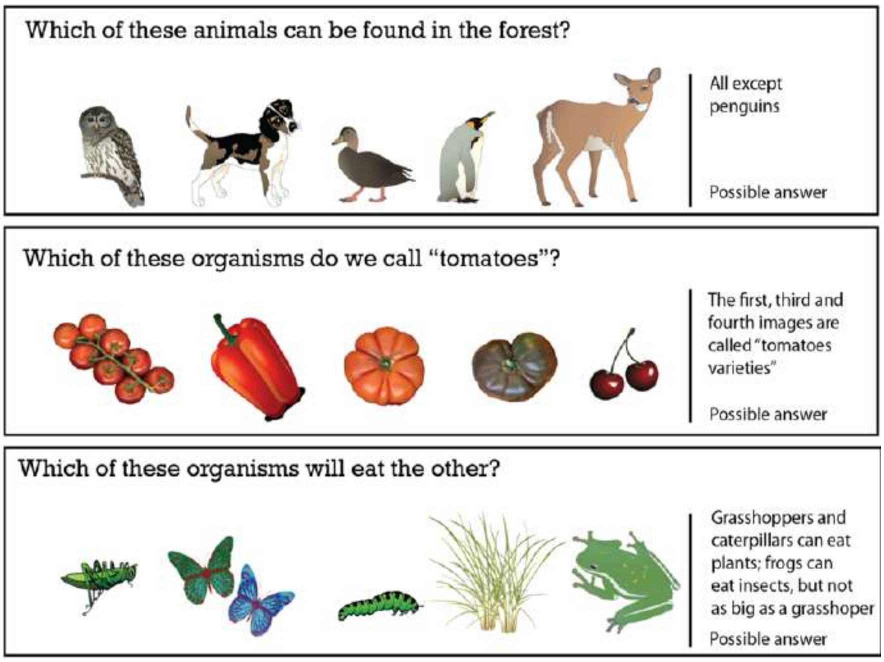

Fig. S3.3: Goal-oriented alternative puzzles with multiple answers in which diversity is acknowledged and can be perceived as positive or neutral attributes of a system.

Fig. S3.4: Experiencing biodiversity in common gardens where neighbors care for shared spaces (Switzerland). ©V.Weber de Melo

Appendix 3

List of studies reviewed for the section "Experiencing biodiversity through food"

Prokop, P. & Fančovičová, J. The perception of toxic and non-toxic plants by children and adolescents with regard to gender: implications for teaching botany. *J. Biol. Educ.* **53**, 463–473 (2019).

Fischer, L. K. *et al.* Biodiverse edible schools: Linking healthy food, school gardens and local urban biodiversity. *Urban Green Infrastruct. – Connect. People Nat. Sustain. Cities* **40**, 35–43 (2019).

Snapp, S. *et al.* Unpacking a crop diversity hotspot: farmer practice and preferences in Northern Malawi. *Int. J. Agric. Sustain.* **17**, 172–188 (2019).

Clark, D. N., Jones, D. N. & Reynolds, S. J. Exploring the motivations for garden bird feeding in south-east England. *Ecol. Soc.* **24**, (2019).

Zhang, W., Zhao, J. & Chen, J. Nature club programs promote adolescents' conservation behavior: A case study in China's biodiversity hotspot. *J. Environ. Educ.* **50**, 192–207 (2019).

Rose, D., Heller, M. C. & Roberto, C. A. Position of the Society for Nutrition Education and Behavior: The Importance of Including Environmental Sustainability in Dietary Guidance. *J. Nutr. Educ. Behav.* **51**, 3-15.e1 (2019).

Raymond, C. M., Diduck, A. P., Buijs, A., Boerchers, M. & Moquin, R. Exploring the co-benefits (and costs) of home gardening for biodiversity conservation. *Local Environ.* **24**, 258–273 (2019).

Zelenika, I., Moreau, T., Lane, O. & Zhao, J. Sustainability education in a botanical garden promotes environmental knowledge, attitudes and willingness to act. *Environ. Educ. Res.* **24**, 1581–1596 (2018).

Nogeire-McRae, T. *et al.* The Role of Urban Agriculture in a Secure, Healthy, and Sustainable Food System. *BioScience* **68**, 748–759 (2018).

Artmann, M. & Sartison, K. The Role of Urban Agriculture as a Nature-Based Solution: A Review for Developing a Systemic Assessment Framework. *Sustainability* **10**, (2018).

Cerda, C. & Bidegain, I. Spectrum of concepts associated with the term "biodiversity": a case study in a biodiversity hotspot in South America. *Environ. Monit. Assess.* **190**, 207 (2018).

Cantor, A. R., Chan, I. & Baines, K. From the Chacra to the Tienda: Dietary delocalization in the Peruvian Andes. *Food Foodways* **26**, 198–222 (2018).

Fančovičová, J. & Prokop, P. Effects of Hands-on Activities on Conservation, Disgust and Knowledge of Woodlice. *Eurasia J. Math. Sci. Technol. Educ.* **14**, 721–729 (2018).

Gbedomon, R. C. *et al.* Functional diversity of home gardens and their agrobiodiversity conservation benefits in Benin, West Africa. *J. Ethnobiol. Ethnomedicine* **13**, 66 (2017).

Ahmed, S. *et al.* Building student capacity to lead sustainability transitions in the food system through farm-based authentic research modules in sustainability sciences (FARMS). *Elem Sci Anth* **5**, 46 (2017).

Meyer, N. & Reguant-Closa, A. "Eat as If You Could Save the Planet and Win!" Sustainability Integration into Nutrition for Exercise and Sport. *Nutrients* **9**, (2017).

Shukla, S., Barkman, J. & Patel, K. Weaving indigenous agricultural knowledge with formal education to enhance community food security: school competition as a pedagogical space in rural Anchetty, India. *Pedagogy Cult. Soc.* **25**, 87–103 (2017).

Specht, K., Siebert, R. & Thomaier, S. Perception and acceptance of agricultural production in and on urban buildings (ZFarming): a qualitative study from Berlin, Germany. *Agric. Hum. Values* **33**, 753–769 (2016).

Barreau, A., Ibarra, J.T., Wyndham, F.S., Rojas, A. & Kozak, R.A. How Can We Teach Our Children if We Cannot Access the Forest? Generational Change in Mapuche Knowledge of Wild Edible Plants in Andean Temperate Ecosystems of Chile. *J. Ethnobiol.* **36**, 412–432 (2016).

Walther, B. A. *et al.* Biodiversity and health: Lessons and recommendations from an interdisciplinary conference to advise Southeast Asian research, society and policy. *Infect. Genet. Evol.* **40**, 29–46 (2016).

Penafiel, D. *et al.* Barriers to Eating Traditional Foods Vary by Age Group in Ecuador With Biodiversity Loss as a Key Issue. *J. Nutr. Educ. Behav.* **48**, 258-268.e1 (2016).

Miranda, J. *et al.* Interdisciplinary and Participatory Research at Early Childhood to Biodiversity Education and Sustainable Development. in *Biodiversity and Education for Sustainable Development* (eds. Castro, P., Azeiteiro, U. M., Bacelar-Nicolau, P., Leal Filho, W. & Azul, A. M.) 265–285 (Springer International Publishing, 2016). doi:10.1007/978-3-319-32318-3_17.

Cox, D. T. C. & Gaston, K. J. Likeability of Garden Birds: Importance of Species Knowledge & Richness in Connecting People to Nature. *PLOS ONE* **10**, e0141505 (2015).

Moleón, M. & Sánchez-Zapata, J. A. The Living Dead. *BioScience* **65**, 1003–1010 (2015).

Bertran Arroyo, E. Management analysis and socio-cultural assessment of community urban gardens in the city of Cordoba (Spain). *Rivar Revista Iberoamericana de viticultura agroindustria y ruralidad* **2**, (2015).

Arias, R. I. Use of Ecuadorian Amazon agro-biodiversity and human academic formation. *Revista Geografica Venezolana* **56**, 205–220 (2015).

Wals, A. E. J., Brody, M., Dillon, J. & Stevenson, R. B. Convergence Between Science and Environmental Education. *Science* **344**, 583 (2014).

Guitart, D. A., Pickering, C. M. & Byrne, J. A. Color me healthy: Food diversity in school community gardens in two rapidly urbanising Australian cities. *Health Place* **26**, 110–117 (2014).

Swierk, L. & Madigosky, S. R. Environmental Perceptions and Resource use in Rural Communities of the Peruvian Amazon (Iquitos and Vicinity, Maynas Province). *Trop. Conserv. Sci.* **7**, 382–402 (2014).

Yli-Panula, E. & Matikainen, E. Students and student's teachers ability to name animals in ecosystems: a perspective of animal knowledge and biodiversity. *J. Balt. Sci. Educ.* **13**, (2013).

Keding, G. B., Schneider, K. & Jordan, I. Production and processing of foods as core aspects of nutrition-sensitive agriculture and sustainable diets. *Food Secur.* **5**, 825–846 (2013).

Braga, H. de O. & Schiavetti, A. Attitudes and local ecological knowledge of experts fishermen in relation to conservation and bycatch of sea turtles (reptilia: testudines), Southern Bahia, Brazil. *J. Ethnobiol. Ethnomedicine* **9**, 15 (2013).

Dor-Haim, S., Amir, R. & Dodick, J. What do Israeli high school students understand about biodiversity? An evaluation of the high school biology programme, 'Nature in a World of Change'. *J. Biol. Educ.* **45**, 198–207 (2011).

Caporali, F. Agroecology as a Transdisciplinary Science for a Sustainable Agriculture. in *Biodiversity, Biofuels, Agroforestry and Conservation Agriculture* (ed. Lichtfouse, E.) 1–71 (Springer Netherlands, 2011). doi:10.1007/978-90-481-9513-8_1.

Kjørstad, I. Slow Food: counteracting fast food and fast living: Case Studies in Sustainable Consumption and Production — Food and Agriculture. *System Innovation for Sustainability* **3**, (2010).

Burlingame, B., Charrondiere, R. & Mouille, B. Food composition is fundamental to the cross-cutting initiative on biodiversity for food and nutrition. *7th Int. Food Data Conf. Food Compos. Biodivers.* **22**, 361–365 (2009).

Rivera, D. *et al.* Disseminating Knowledge about 'Local Food Plants' and 'Local Plant Foods'. in *Forum of Nutrition* vol. 59 75–85 (2006).

4. Chapter 2 - Systemic analysis of interactions between land use change, biodiversity, productivity and nutrition

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4.1 Abstract

The transformation of land for human activities is a major global-change driver that affects biodiversity and ecosystem productivity and tightly relates to population well-being. Policy makers and practitioners require detailed quantitative information for holistic socio-ecological systems, in order to tailor policies that tackle major challenges of our time: global change, biodiversity loss and poverty. In this paper, we propose a systemic approach to better understand the relationships occurring in the socio-ecological system between four interconnected variables: land-use (LU), biodiversity (BD), net primary productivity (NPP) and nutritional status of communities (NUT). This system contains sixteen possible effects of one variable on another and each variable onto itself.

Our exploratory analysis was done with a systematic literature search on each interaction. To be used in a meta-analysis, the direction of the effect should have been clear from the experimental design, and analyses and reported results should have included means of treatment and control, errors and number of observations, which is required to calculate a log response ratio as an effect size. We found sufficient studies with these characteristics for four of those relationships: (number of observations: LU->BD: 317, LU->NPP: 75, BD->NPP: 29, LU->NUT: 15). On these we performed a meta-analysis to investigate overall effects and the influence of contextual variables modifying these effects.

Results suggest that, on average: a) land-use change has large negative effects on biodiversity (causing between 15% and 23% decline), b) land-use change has variable effects on productivity (between 22% decline and 1% increase), c) land-use change has overall positive effects on the nutritional status of communities, more than a 100% increase, but the estimate was possibly biased by the limited number of quantitative studies), and d) biodiversity increases have a large positive effect on productivity (58% increase). We did not find studies addressing the effect of nutritional status changes on land-use change, but we found numerous qualitative studies on how diet changes, a potential proxy for nutritional status, may change land-use practices (through consumer demands). Since we considered this link relevant, we included a qualitative review on effects of diet shifts on land-use change, which overall suggests that education about nutrition and shifts to nutrition-sensitive agriculture could aid in reducing our environmental impact.

For the quantitative analyses, we included the following contextual variables (modifiers): type of land use (e.g., animal pasture, cropping), type of ecosystem (e.g., grassland, forest), and type of taxonomic group where biodiversity was measured (e.g., insects, mammals). In general, we found that the largest negative impacts on biodiversity were driven by animal pasture, on grasslands, and on invertebrates. However, some of these results may be biased by the availability of studies per activity, ecosystem and taxonomic group, which was uneven: the majority of animal-pasture studies were performed in forests and overall the studies were largely performed in grasslands.

We identified challenges in data synthesis for interdisciplinary networks of variables such as lack of standardized measures (e.g., to define intensity of land use), ambiguous terminology (e.g., various definitions for land-use practices and ecosystems), and incomplete reporting of data and their accuracy. Overall, this study highlights the potential of and challenges for systemic analysis to help understand complex socio-ecological systems as a means to better manage and predict changes in these systems.

Keywords: global change; integration; data sharing; interdisciplinarity; socio-ecological systems

4.2 Introduction

Humanity faces a great number of global challenges: achieving sustainable development, reducing poverty, climate-change threats and loss of biodiversity, among others. For the past 20 years, international organizations have successfully raised awareness on the importance of addressing these issues globally and in an interdisciplinary way (CBD, 2010; MEA, 2005). In parallel, scientific efforts have been oriented to identify and study socio-ecological systems that are affected by these challenges, generating substantial amounts of data (Tenopir et al., 2011).

Socio-ecological systems are complex by nature: there are many variables that interact with one another and feed back onto themselves at different spatial and temporal scales (Chapin et al., 2008; Liu et al., 2015; Wu, 2004). Furthermore, the view of the scientific community on how to approach these systems is not static; it evolves as more and deeper information comes to light (Zuppinger-Dingley et al., 2017). Hence, there is a pressing need for periodic reviews and integrative analyses to help establish priorities, single out knowledge gaps and possibly make suggestions for a better management of socio-ecological systems under global change.

Global change is a term that refers to the group of processes from natural and anthropogenic origins that affect the Earth and possibly its capacity to sustain life (Steffen et al., 2005). The complexity of global-change phenomena requires developing suitable frameworks of study. In the present study, we used a framework adapted from the Millennium Ecosystem Assessment, in which global-change variables are classified in four compartments: drivers, biodiversity measurements, ecosystem variables, and well-being indicators (Fig. 4.1).

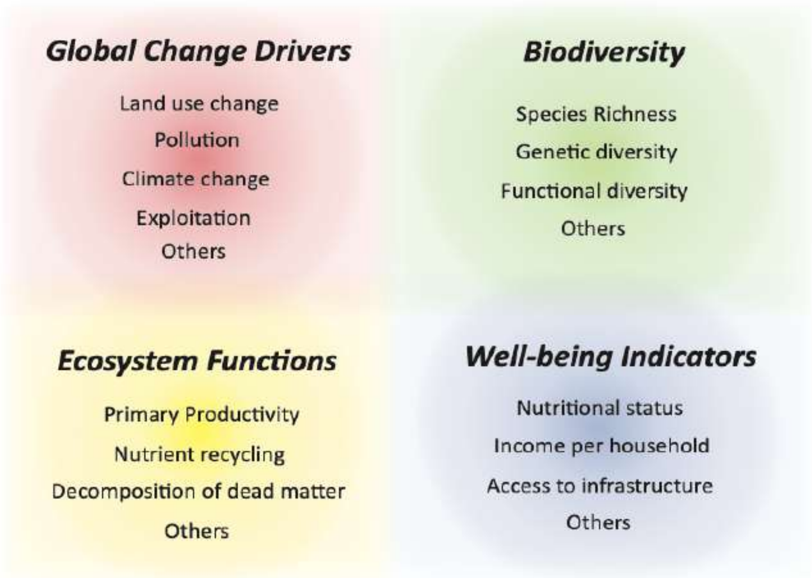

Fig. 4.1: Classification of variables related to global change in four compartments. Adapted from the Millennium Ecosystem Assessment (MEA, 2005) and the proposal for the University Research Priority Program Global Change and Biodiversity (URPP GCB, 2012).

Global-change drivers are phenomena that have been identified to be key forces in shaping natural systems (Sala et al., 2000). Five of them have been singled out as the ones that require a most urgent response: climate change, invasive species, pollution, land-use change, and resource exploitation (CBD, 2010). Among these, climate change and land-use change are recurrent issues for policy and governance (Godfray & Garnett, 2014; Sala et al., 2000). The effects of land-use change on biodiversity vary in magnitude and rate globally and are usually associated with biodiversity loss or shifts in biodiversity composition, which in turn may change ecosystem functioning (Laland & Boogert, 2010; Walther et al., 2002). Humans modify the land in order to increase productivity and human well-being. However, there is great uncertainty about the long-term outcomes of our interventions, both in terms of biomass (productivity) and improvement of human well-being (Ramankutty et al., 2018; Saladini et al., 2018).

The term *ecosystem function/functioning* is used in ecology when referring to the biogeochemical processes that occur at ecosystem level, although other alternative uses for the term *function* have often been employed in the literature (Jax & Setälä, 2005). *Ecosystem variables* that can affect human well-being have been defined as *ecosystem services* (see e.g. Balvanera et al. 2006). In the present study we refer to ecosystem variables when discussing biogeochemical processes such as primary productivity, decomposition, and nutrient cycling, separate from their role as ecosystem services (even when we acknowledge the connection between the two) (Kremen & Ostfeld, 2005; Spangenberg et al., 2014). From all the ecosystem variables defined, "net primary productivity" is arguably one of the most relevant ones, as it describes the energy, nutrient, and biomass flows that drive most other ecosystem processes (Chapin & Eviner, 2007). The main producers of biomass in terrestrial ecosystems are green plants, which are at the base of the trophic chains (Roy et al., 2001). Land-use change due to human activities such as agriculture, forestry, and urbanization, affect the global productivity of ecosystems, with further feedbacks on climate change and other global drivers (Lambin & Meyfroidt, 2011; Leng & Huang, 2017).

In our framework (Fig. 4.1), biodiversity is singled out from ecosystem variables or processes, given its relevance as a feature across several if not all of them (Cardinale et al., 2012; Flynn et al., 2011; Isbell et al., 2011). Several studies found that the multi-functionality of ecosystems requires higher levels of biodiversity than what can be found when studying variables in isolation, such as ecosystem productivity (Balvanera et al., 2006; Blüthgen & Klein, 2011; Cardinale et al., 2012; Hector & Bagchi, 2007; Isbell et al., 2011; Lefcheck et al., 2015; Manning et al., 2018; Zavaleta et al., 2010). The relationship between the number of species in a system and its productivity has been the center a long debate in ecology: is biodiversity increasing, decreasing or not relevant to the level of productivity of a system? (Mittelbach et al., 2001; Waide et al., 1999). A recent review on the relation between biodiversity and productivity and competition for resources in plants sheds light on the large number of hypotheses that have been proposed, but also on how relatively few times they have been experimentally tested given the difficulty to establish the direction of causalities (Parreño et al., in preparation). Furthermore, human well-being has been linked with biodiversity, and the strength of this interaction has sometimes been quantified through socio-economic indexes, such as those targeting education levels or GDP, or through the provision of ecosystem services (Naeem et al. 2016).

Well-being indicators measure outcomes of land-use interventions in ecosystem management, often in relation to biodiversity change (Loreau et al. 2002, Naeem et al 2016). Improving the nutritional status is a common aim in land-use programs such as those promoting nutritional education, food supplement, nutrition rehabilitation or improved agricultural production (Fleuret & Fleuret, 1980). Even more, land-use programs that explicitly include health and nutrition as an endpoint are sometimes called nutrition-sensitive agriculture (NSA) (Allen et al., 2014; Maluf et al., 2015).

Nevertheless, it is often difficult to measure effects of land-use change on nutritional status, given the multidimensional nature of the concept of “nutrition”, and to account for the various contextual variables such as natural phenomena (e.g., weather fluctuations and seasonality of crops) and societal aspects (cultural values) that simultaneously have direct and indirect effects on an observable outcome. For example, some studies highlight the role of crop diversification, gender issues and nutrition education as important modifiers that determine the outcome of these projects in agriculture and nutrition (Cunningham et al., 2015; Wenhold et al., 2007). Others focus on the impact that the quality of landscape resources (soil nutrients, water) has on agricultural success and food security (Chakona & Shackleton, 2018; Mohsena et al., 2018). The multidisciplinary nature of the complex socio-ecological issue of food and nutrition security means that people used to working with different terminologies, from diverse academic backgrounds, and that usually take different approaches must sit together and agree on ways forward in research and practice (Hammond & Dubé, 2012).

Quantitative reviews have a number of benefits over qualitative ones. A type of quantitative review, meta-analysis, has seen a rise in importance as a tool for systematic research in ecology for the past 20 years (Koricheva et al., 2013). Several authors have used meta-analysis to address the particular relationships between variables of global change (Balvanera et al., 2006; Hooper et al., 2012; Paquette & Messier, 2011; Rustad et al., 2001). In contrast, there are not many studies that have taken into account relationships between variables of four compartments at the same time, despite its importance being stressed in policy documents. Understanding the effects between these variables is of relevance to making predictions on the evolution of socio-ecological systems under global change.

In this context, we aim to answer the following questions:

- What is the strength and direction of effects between land-use change, biodiversity, productivity and people's nutritional status?
- When it is not possible to perform a quantitative review: what is the type of conclusions that can be derived with available literature?

4.3 Methods

a) Definition of variables and relationships

A list of the variables and sub-variables included in the present analysis is shown in Table 4.1. Detailed definitions can be found in the protocol and glossary (Appendix S3) (Note: all appendices, figures and tables with an S in front, are in the supplementary material).

Table 4.1: List of variables included in the analysis of socio-ecological systems.

Compartment	Variable group	Variable
Global-change drivers	Land-use change	Cropping, forestry, animal pasture, agroforestry
Indicators of well-being	Nutritional status	Vitamin A, vitamin C, anthropometric indexes
Biodiversity	Biodiversity measurements	Species richness, evenness, Shannon index
Ecosystem variables	Primary productivity	Primary productivity, biomass

Figure 4.2 shows a causal-loop diagram of a socio-ecological system, with all possible relationships between variables (a) and the ones finally explored (b).

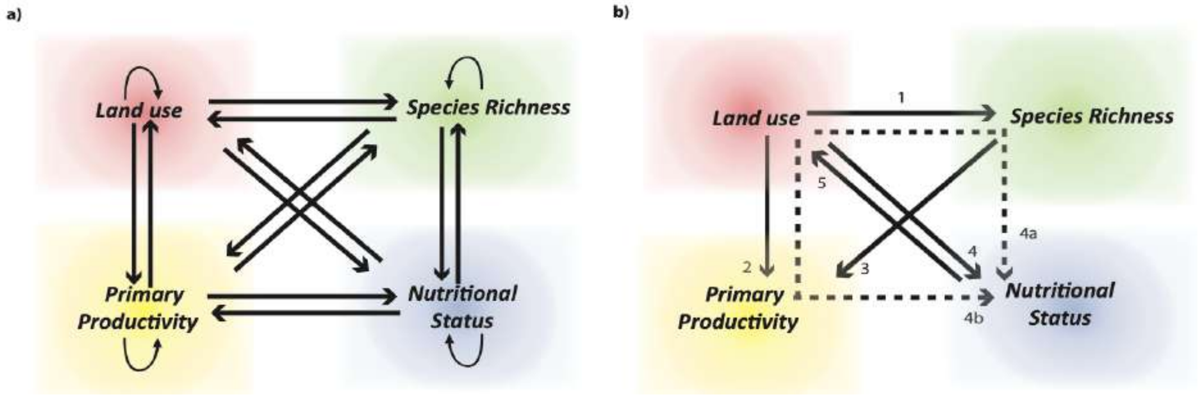

Fig. 4.2: Network diagrams for the socio-ecological system of interest. a) diagram of all 16 possible relationships in the system, b) diagram of relationships analyzed in our study based on an exploratory literature search, numbered as presented in Methods and Results sections.

b) Search strategies

We developed a search strategy and protocol for literature acquisition through systematic review (Appendix S3). We used the search engine "Web of Science" and browsed in the titles, abstracts, and keywords of papers from the year 2000 onwards using keywords that related to each pairwise interaction of interest. The literature review was *non-exhaustive*, given that we wanted to perform an exploratory study of numerous variables within this system. This means that not all of the papers we found were read for this particular study; we read until we found sufficient studies to perform a meta-analysis. We sorted the list of studies by relevance and read papers in order with the aim of reaching more than 30 quantitative observations/effects (the number of papers could be less because some contained multiple independent observations, e.g., different locations). However, this was not always possible, so we worked with available information. Initially, we explored the availability of literature for relationships in both directions (Fig. 4.2a). Then we focused on the ones for which we found enough papers with clear indications of causality between variables (Fig. 4.2b). A detailed list of exclusion/inclusion criteria is provided in Appendix S3.

c) Data extraction for meta-analyses

First, we defined control and treatments for each interaction. We decided to split the dataset to increase the potential for comparison between studies and reduce heterogeneity in an already highly heterogeneous dataset (given the number of human activities taken into account). This decision was backed up by literature that found that the presence of human activities determining landscape structure, connectivity, and geo-morphology affects the distribution and richness of many species, by facilitating invasion or favoring competitor species conducing to population reductions or extinctions (Luther et al., 2008). Furthermore, disturbances of landscapes can alter the dynamics of ecosystem processes (Turner, 2010).

The list of controls and treatments per relationship are:

- **Land-use type effects on biodiversity or productivity (LUT->BD and LUT->NPP):** control is a native patch of land and treatment is a human-modified patch (the separation is spatial, not temporal).
- **Land-use intensity effects on biodiversity or productivity (LUI->BD and LUI->NPP):** there is a human activity in both control and treatment land patches but the one in the treatment is performed at higher intensity (the separation is spatial, not temporal; there are only two levels of intensity: control vs. high). Note: not to confuse with the modifier intensity which was designed to account for the different strength of intensity within the LUT or LUI treatments (i.e. excluding controls) and which varied from low to intermediate to high.
- **Biodiversity effects on productivity (BD->NPP):** control is a plot of land with less biodiversity (fewer number of species present), and treatment is a plot with greater biodiversity.
- **Land-use alteration effects on nutritional status (LUA->NUT):** control is a patch of land that is not native but is also not being used for a productive human activity (e.g., an abandoned garden). Treatment is a human activity aimed at increasing productivity and biodiversity (i.e., gardening for food in urban or semi-rural spaces). The control and treatment for land use are different based on the studies found (they were redefined after the literature search): we found no studies for this effect where land-use activities were intensified.

We built a dataset of means, errors, and number of observations for the response variables of each pairwise relationship, extracted from result sections or supplementary material of original publications or personal communication with authors. We did not use the slope of relationships in studies with gradients, since we aimed to use effect sizes that require means as an input (for example: Hedges'g – Standarized Mean Difference or log-response ratio). From studies that presented relationships with proof of causality (e.g., due to their manipulative experimental design), we used the means and errors at the extreme points as if they had been discrete control and treatments.

From each study we also extracted information about the following contextual variables to be used as modifiers, when available: type of study (observational field surveys or manipulative experiments), type of land use within LUT or LUI, intensity of land use within LUT or LUI (with levels low, intermediate, and high according to the original authors, not available for all citations), type of ecosystem, and type of biodiversity (taxonomic group for which diversity was measured).

d) Analyses

We calculated an effect size for each study. We used the log-response ratio as measure of effect size (ln RR) for all studies using a control and treatments, as follows:

- Land-use effects on biodiversity (LUI/LUT->BD): Effect size: ln RR $$\frac{BD_{\text{Modified}}}{BD_{\text{Low intensity/ Native}}}$$
- Land-use effects on productivity (LUI/LUT->NPP): Effect size: ln RR $$\frac{NPP_{\text{Modified}}}{NPP_{\text{Low intensity/ Native}}}$$
- Biodiversity effects on productivity (BD->NPP): Effect size: ln RR $$\frac{NPP_{\text{High biodiversity}}}{NPP_{\text{Low biodiversity}}}$$
- Land-use alteration on nutritional status (LUA->NUT): Effect size: ln RR $$\frac{NUT_{\text{LU intervention}}}{NUT_{\text{No LU intervention}}}$$

We removed those observations in which the variance tended to infinity (because sampling variance was zero or due to lack of replication) (as recommended by Prof. Julia Koricheva, personal communication). The number of eliminated observations was: LUT->BD: 13; LUI->BD: 2; LUT->NPP: none; LUI->NPP: 4; BD->NPP: none; LU->NUT: none). The weights for the effect sizes were calculated with the default option for the function rma.mv (metafor), which is based on the sampling variances of studies (Viechtbauer, 2010b). A correction for small sample sizes was performed on all effects, using the Delta Method (Lajeunesse, 2015).

Firstly, we calculated an average effect size across studies, using meta-analysis. To control for non-independence caused by one citation reporting several studies, we ran a multilevel meta-analysis, using citation as a random effect (Koricheva & Gurevitch, 2014). We back-transformed log ratios, and expressed them as percent of change in the response variable, for easier interpretation. We used 95% confidence intervals as error.

Secondly, we examined the sources of between-study heterogeneity, using meta-regression with the contextual variables (from now on *modifiers*) extracted from studies, a) first in a model with multiple modifiers (and we evaluated different models), and then b) each modifier independently, so as to explore differences between levels (Borenstein et al., 2009).

All analyses were performed with R Software (R Development Core Team, 2013). The calculation of average effects and meta-regressions to test modifiers was performed with the *metafor* package (Viechtbauer, 2010a), whereas multiple comparisons between linear hypotheses were performed with *multcomp* package (Bretz et al., 2010). Plots were made with the *forestplot* package (Gordon & Lumley, 2019) and *ggplot2* (Wickham, 2016). Publication bias was assessed with funnel plots, fail safe-n tests (Rosenthal, 1979) and Egger tests (Egger et al., 1997). Collinearity in the multiple regressions was assessed with the variance inflation factor (VIF) (Thompson et al., 2017).

4.4 Results

Structure of the results section

The results section is structured in the following way: a) overview of network: summary of the outcomes for all relationships of the network (number of studies and average effects); b) detailed results per pairwise relationship: in-depth meta-analysis, including meta-regressions with modifiers.

a) Average effects in all relationships

Table 4.2 and Figure 4.3 are summaries that show the average effects for all meta-analyses performed. Effects are back-transformed for easy interpretation (e.g., land-use type caused a decline of 23% in biodiversity). The test for heterogeneity between citations was large and significant for all relationships.

All effects were significant, except the one of land-use intensity (LUI) on productivity (due to large variance between citations). Land-use type and land-use intensity (LUI) had overall negative effects on biodiversity and productivity, whereas biodiversity increase had a positive effect on productivity and land-use alteration (LUA) had a large positive effect on nutrition.

Table 4.2: Information on average effect size per relationship. Effect size is log ratio of means, back-transformed with an exponential function and expressed in percentage of change. Significance: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-). SE: Standard error, N studies: number of independent studies (and citations), Q: Q-heterogeneity test (i.e. measure for residual variation among citations; note that this residual variation may in part be explained by modifiers), df= degrees of freedom, ci.lb/ci.ub: 95% confidence intervals)

Effect	N studies (citations)	Back-transformed effect (%) 95%CI	Q(df=n-1)	ln RR (Effect size) +/-SE, (ci.lb, ci.ub)
Land-use type effect on Biodiversity	99 (21)	-23.35* (-41.07 to -0.33)	2845.02*	-0.27 +/- 0.13 (-0.53 to -0.003)
Land-use intensity effect on Biodiversity	218 (39)	-15.81*** (-22.55 to -8.48)	2237.65***	-0.17 +/-0.04 (-0.25 to -0.09)
Land-use type effect on Productivity	37 (4)	1,21^{ns} (-54.26 to 123.96)	6385.07***	0.012+/-0.405 (-0.78 to 0.81)
Land-use intensity effect on Productivity	38 (6)	-22.43** (-35.07 to -7.32)	541.04***	-0.25+/-0.09 (-0.43 to 0.08)
Biodiversity effect on Productivity	29 (7)	57.63*** (25.42 to 98.12)	178.54***	0.45+/-0.12 (0.23 to 0.68)
Land-use alteration effect on Nutritional status	15 (7)	142.561* (119.76 to 169.71)	356.94***	0.35 +/- 0.17 (0.013 to 0.69)

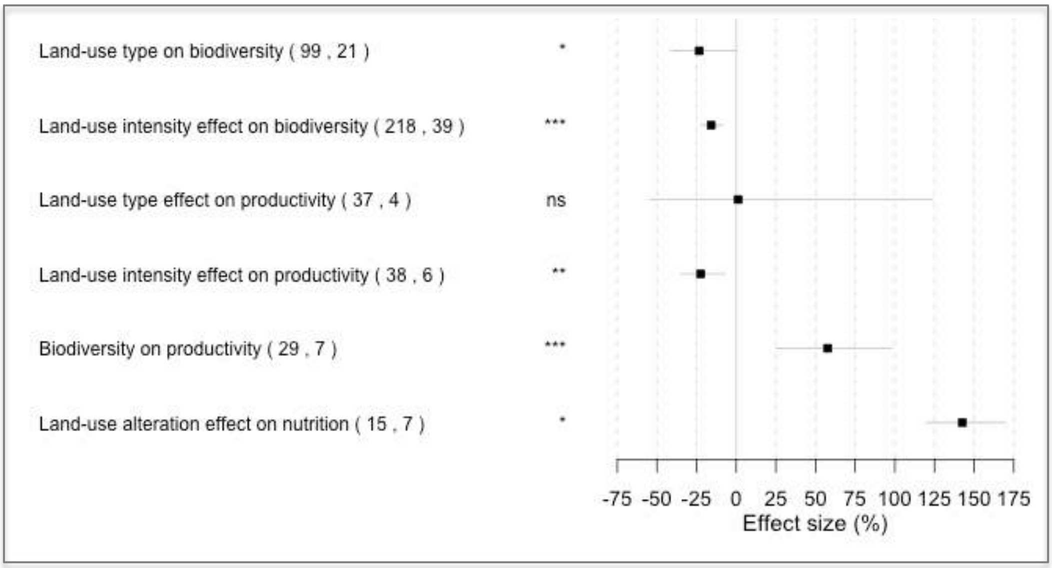

Fig. 4.3: Average size of each effect (+/- 95% CI). In parenthesis: number of studies and citations. Significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (ns).

b) Detailed results per pairwise relationship

b.1) LUT and LUI effects on biodiversity

We found 8644 papers of which we read 753 and from those, 62 papers met our criteria for the meta-analysis (we included more than 30 papers to increase representation of a number of different land-use activities). These 62 citations reported an overall total of 352 effects. We separated the effects into the different land-use changes described in methods:

- Land-use type dataset (LUT: human activity vs. “native”): 120 studies from 22 citations, of which 13 studies had to be eliminated due to lack of sampling variance and one citation (with 8 studies) was eliminated because it was the only one with the taxonomic group fungi. **Total: 99 studies from 21 citations**.
- Land-use intensity dataset (LUI; intensity of human activity high vs. low): 223 studies from 40 citations, from which two studies were eliminated due to lack of sampling variance and one citation (with three studies) was eliminated because it was the only one of agroforestry. **Total: 218 studies from 39 citations**.
- There is no overlap of studies between databases.

Land-use type showed an average negative effect on species richness of -23.35%, with a relatively large variance. Land-use intensity also showed an average negative effect on species richness of -15.81%, with less variance than the land-use type dataset (Table 4.2). No evidence of publication bias was found for either dataset, using funnel plots, fail-safe n, and Egger tests (Fig 4.S1.1, Table 4.S2.1).

For both datasets, a model fitting type of land use, type of ecosystem and taxonomic group of biodiversity as modifiers (in this sequence) showed that all of these modifiers could explain a significantly part of the heterogeneity between studies (Table 4.3 a, b). We did not fit the modifier intensity into the main model given the large amount of missing values (NA). Intensity of land use was analyzed separately in a subset of the dataset for which this information was available.

Table 4.3 (a, b): Anova-type tests for multivariate meta-analysis with sequentially added modifiers. (LTR: Log likelihood ratio between sequential models, the first one fitting the overall mean not shown in the table, df: degrees of freedom)

a) Land-use type effects on biodiversity (LUT -> BD)

Term added to the model	**df**	**LRT**	***P*-value**
Type of land-use	4	339.01	<0.0001
Type of ecosystem	1	7.66	0.0057
Taxonomic group	2	33.26	<0.0001

b) Land-use intensity effects on biodiversity (LUI -> BD)

Term added to the model	**df**	**LRT**	***P*-value**
Type of land-use	3	114.67	<0.0001
Type of ecosystem	2	53.4	<0.0001
Taxonomic group	3	26.72	<0.0001

We then explored each of these modifiers through simple meta-regressions. Note: some citations had studies across multiple types of land use, ecosystems and taxa, therefore the number of studies may not add up to the one for the summary.

Meta-regressions for effects of different modifiers on effects of LUT or LUI on biodiversity

Type of land-use activity

First, we analyzed the influence of different types or intensities of land use (human activity) as modifiers in simple meta-regressions (Fig. 4.4a,b).

- **LUT:** the effects of animal pasture, mixed activities, cropping and agroforestry were significant ($P<0.05$), with animal pasture having the greatest effect on biodiversity loss (more than 60% decline) (Fig. 4.4 a). Regarding non-significant trends, forestry showed a small but positive effect on biodiversity (+2%). Pairwise comparisons between land-use types showed that the effects of mixed activities, cropping and agroforestry were not significantly different from each other ($P>0.05$), but significantly different from animal pasture and all those from forestry.
- **LUI:** animal pasture and cropping showed the largest effects on biodiversity loss (more than 30% decline) (Fig 4b). Regarding non-significant trends, mixed activities and forestry showed a small negative effect on biodiversity (-2%).

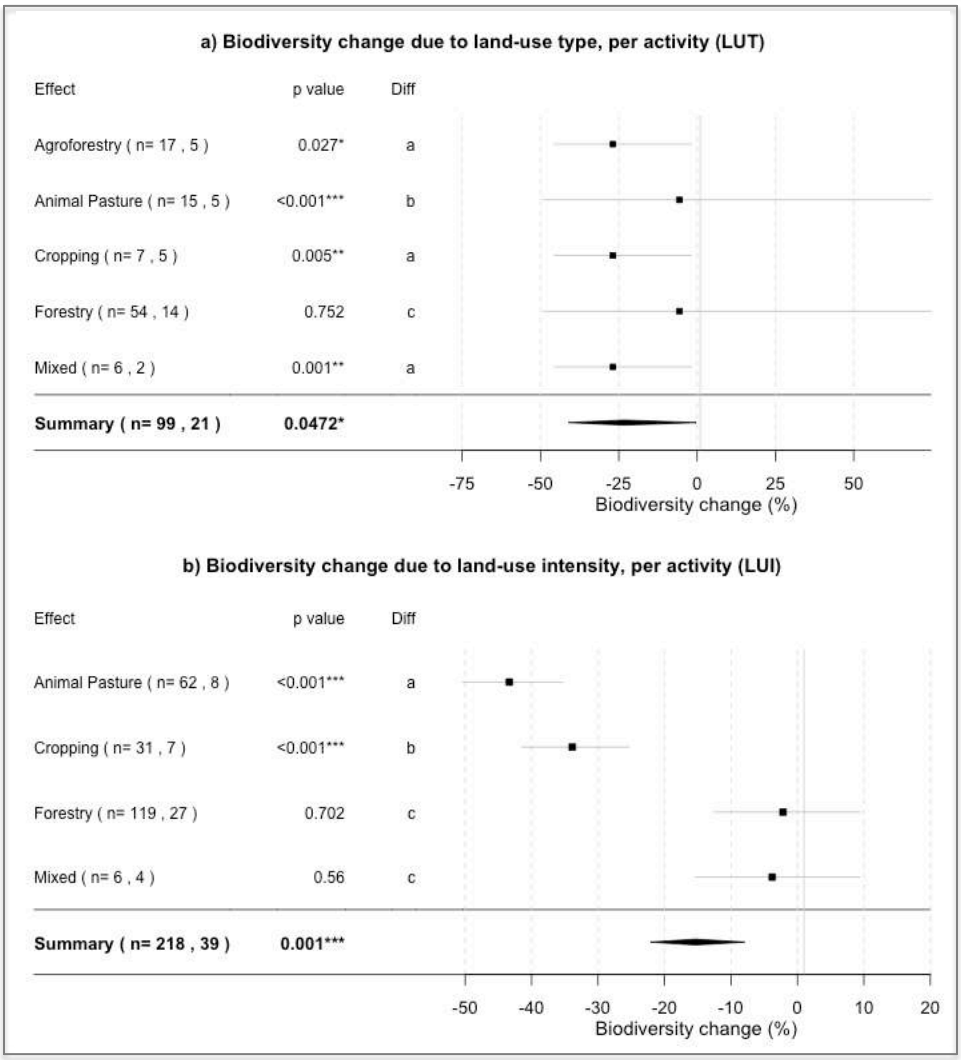

Fig. 4.4: Percent biodiversity change (+/- 95%-CI) in a) land-use type (LUT) and b) land-use intensity (LUI) datasets, per activity type. (n: number of studies and citations, significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-), Diff: different letters indicating pairwise comparisons that are significant and *P*<0.05). Summary (average effect +/- 95%-CI) represented as a rhombus.

Ecosystem

The dataset on land-use type (LUT) has information for two ecosystems: forest and shrubland. When fitting ecosystem as a modifier, we found a significantly negative effect of LUT in forests (-26%, [CI -45; -1.9], *P*<0.05) but not in shrublands (-5.7%, [CI -49; 74], ns), yet the difference in the response between the two was not significant (Fig 4.5a). The dataset on land-use intensity (LUI) has observations in three ecosystems: grassland, forest and shrubland. When testing ecosystem as a sole modifier, results show a negative effect of LUI on all ecosystems, largest in grasslands (-44.59%, [CI -52.47, -35.40], *P*<0.05), then in shrublands (-26.8, [CI -36.76, -15.27], *P*<0.05) and non-significant, but with larger variance, in forests (-2.58, [CI -13.78, 10.06], ns) (Fig. 4.5b).

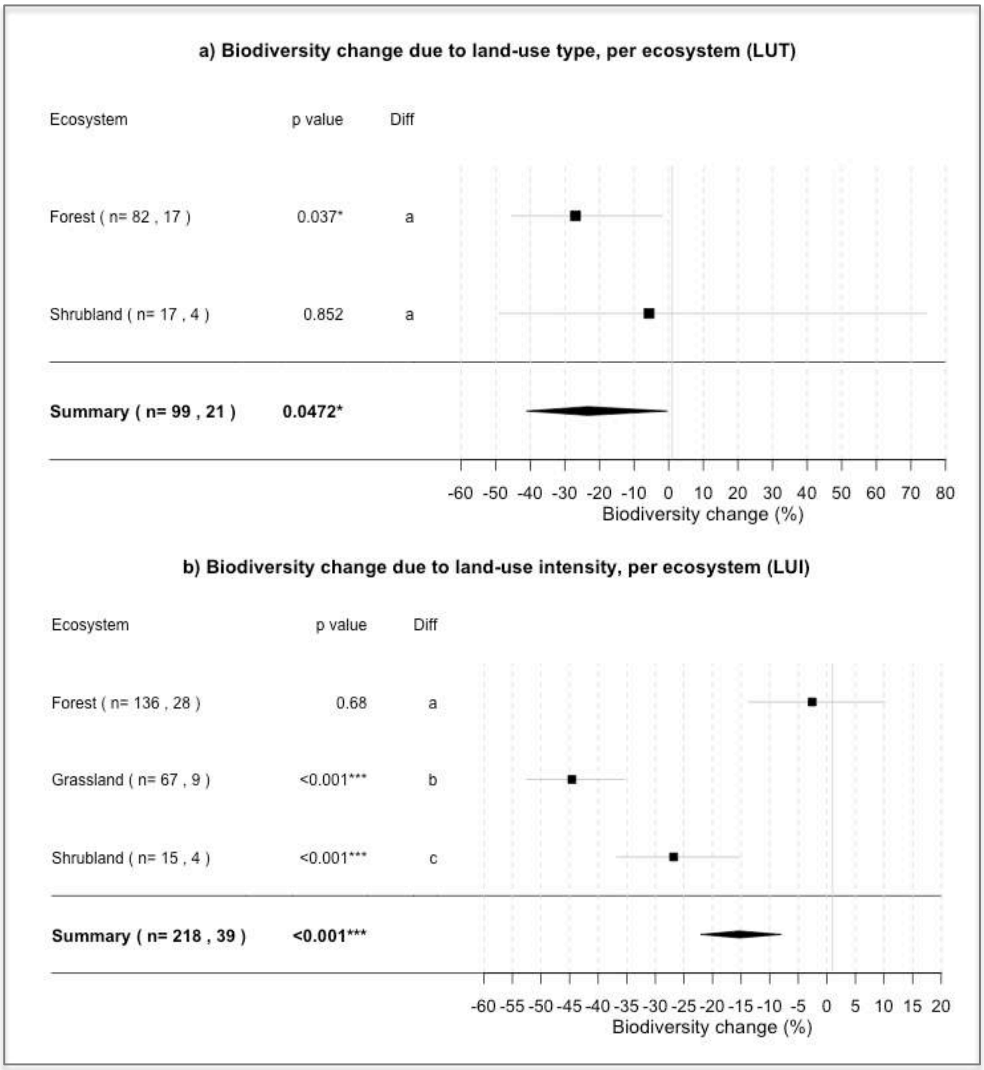

Fig. 4.5: Percent biodiversity change (+/- 95% CI) in a) land-use type (LUT) and b) land-use intensity (LUI) datasets, per ecosystem. (n: number of studies and citations, significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-), Diff: different letters indicating pairwise comparisons that are significant and *P*<0.05). Summary (average effect +/- 95%-CI) represented as a rhombus.

Taxonomic group

The dataset on land-use type (LUT) has observations of effects on biodiversity of invertebrates, vertebrates and plants. When fitting taxa as a modifier, we found a negative effect of LUT on invertebrate biodiversity, different from non-significant effects on vertebrate (positive) and plant biodiversity (negative) (Fig. 4.6a). There was a large variance in the effect on vertebrate and plants groups. The dataset on land-use intensity (LUI) has observations of effects on biodiversity of the same taxa as LUT, as well as for biodiversity of fungi. When fitting taxa as a modifier, results showed negative effects of LUI on the biodiversity of all taxa, with the highest impacts on plants and vertebrates (20% (+/-7; +/-9 respectively) (Fig. 4.6b).

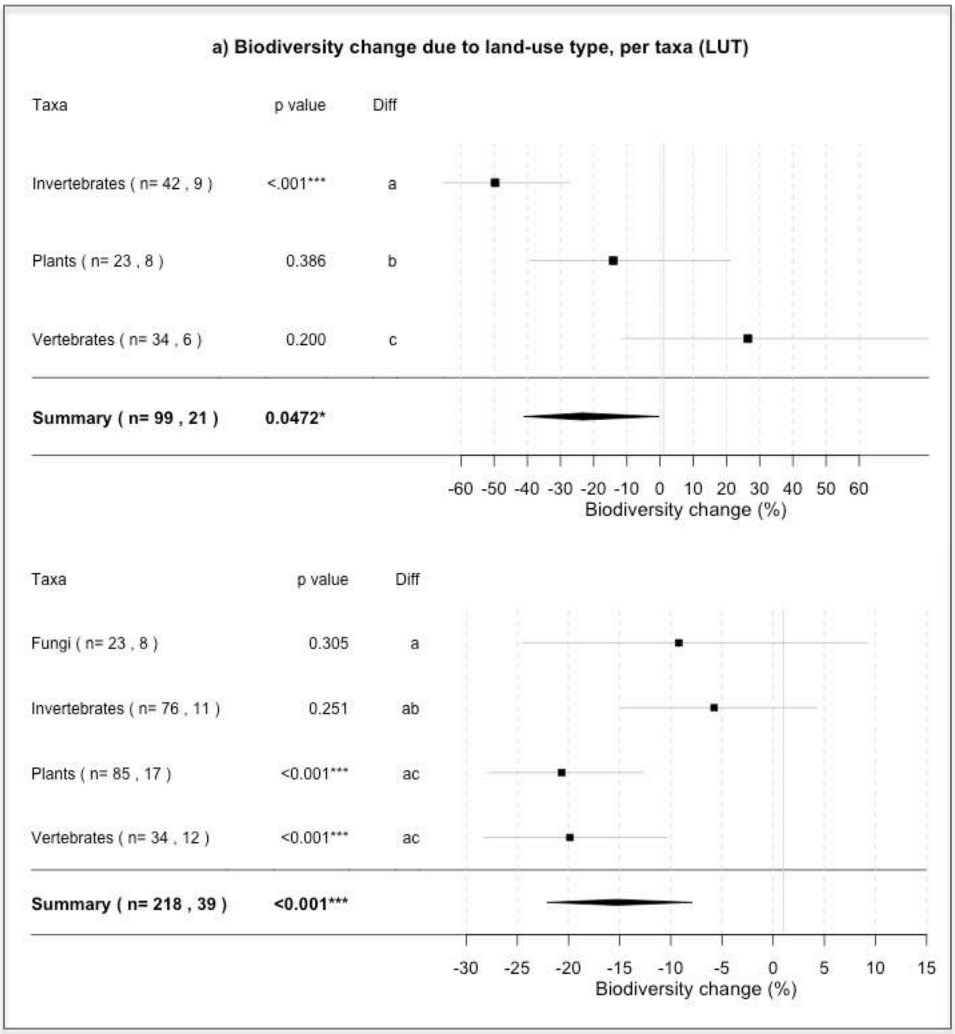

Fig. 4.6: Percent in biodiversity change (average effect +/- 95%-CI), in a) land-use type (LUT) and b) land-use intensity (LUI) datasets, per taxa. (n: number of studies and citations, significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (-), *P*>=0.05 (-), Diff: different letters indicating pairwise comparisons that are significant and *P*<0.05). Summary (average effect +/- 95%-CI) represented as a rhombus.

Land-use intensity

Meta-regression with land-use intensity as a sole modifier, for both reduced datasets of studies, was performed where data were available (Fig. 4.7a,b). Note that this intensity is measured as low, intermediate, or high to compare between papers. While this is the intensity index used as a modifier, the intensity level used for the main analyses defining LUI is not a modifier, it’s a treatment-control comparison. Results showed that effects of land-use type and intensity on biodiversity were significant at intermediate and high intensity but not at low.

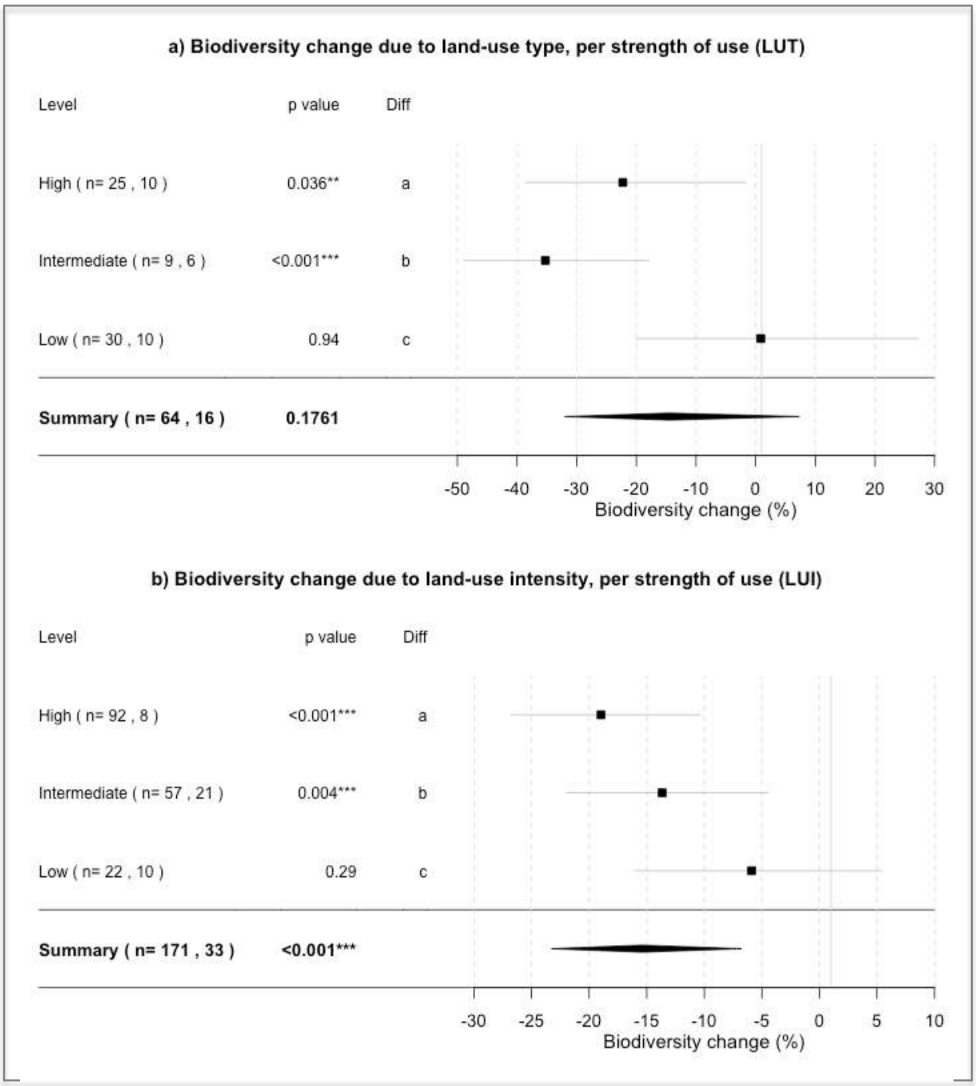

Fig. 4.7: Percent in biodiversity changes (+/- 95%-CI) with intensity levels on a) land-use type (LUT) dataset, b) land-use intensity (LUI) dataset. (n: number of studies and citations, significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-), Diff: different letters indicating pairwise comparisons that are significant and *P*<0.05). Summary (average effect +/- 95%-CI) represented as a rhombus.

b.2) LUT and LUI effects on productivity

We found 5648 papers, from which we read 215 (for a matter of time) and 10 papers of them met our criteria, some of them with several independent studies, leading to an overall total of 79 effects reported (we included more than 30 observations to increase representation of a number of different land-use activities). The rest of the papers were rejected according to protocol (Appendix S3). We separated the database into:

- **LUT: 37 studies from 4 citations**

- **LUI:** 42 studies from 7 citations, from which one citation (4 studies) was deleted due to lack of sampling variance. **Total: 38 studies from 6 citations.**

Land-use type showed an average neutral effect of land use on productivity with a large variance (log-response ratio: 0.0120, se: 0.4053, *P*>0.05); when back-transformed with the exponential function this can be interpreted as a very small 1.2% (-54, +123) increase in land productivity (Table 4.2).

Land-use intensity showed an average negative effect on productivity (log-response ratio: -0.2539, se: 0.0908, *P*<0.01) equivalent to a -22.42% (-35.07,-7.32) decline of productivity. No evidence of publication bias was found for the LUT dataset, using funnel plots, fail-safe n, and Egger tests, but a publication bias could be interpreted from the low fail-safe n (671) and relatively large intercept in the Egger test, for the LUI dataset (Fig 4.S1.1, Table 4.S2.1).

An ANOVA analysis including the modifiers type of land-use change and ecosystem showed that both could explain a significant part of the heterogeneity between studies (Table 4b). Note that for LUT dataset we did not fit type of land-use change because there is only one activity (cropping). We explored each of these modifiers.

Table 4.4 (a, b): Anova-type tests for multivariate meta-analysis with sequentially added modifiers. (LTR: Log likelihood ratio between sequential models, the first one fitting the overall mean not shown in the table, df: degrees of freedom)

a) Land-use type effects on biodiversity (LUT-Productivity-NPP)

Term added to the model	df	LRT	p-value
Type of ecosystem	2	627.11	<.0001

b) Land-use intensity effects on biodiversity (LUI-Productivity-NPP)

Term added to the model	df	LRT	p-value
Type of land use	2	93.6189	<.0001
Type of ecosystem	2	0.2682	0.8745 ns

Meta-regressions for effects of different modifiers on effects of LUT or LUI on productivity

Type of land-use activity

We performed meta-regressions using different types or intensities of land use as modifiers (Fig. 4.8a,b).

a) **LUT:** all observations in the land-use type dataset involved comparing native land to agriculture (cropping), which showed a small positive effect on productivity, although with a large variance around that effect. Thus, this term could not be fit as a modifier for the LUT dataset.

b) **LUI:** in this dataset there were observations for cropping, animal pasture, and mixed activities. Intensity of animal pasture had a negative impact on biodiversity, while intensity of cropping and mixed activities had a small but positive one (although with a large variance).

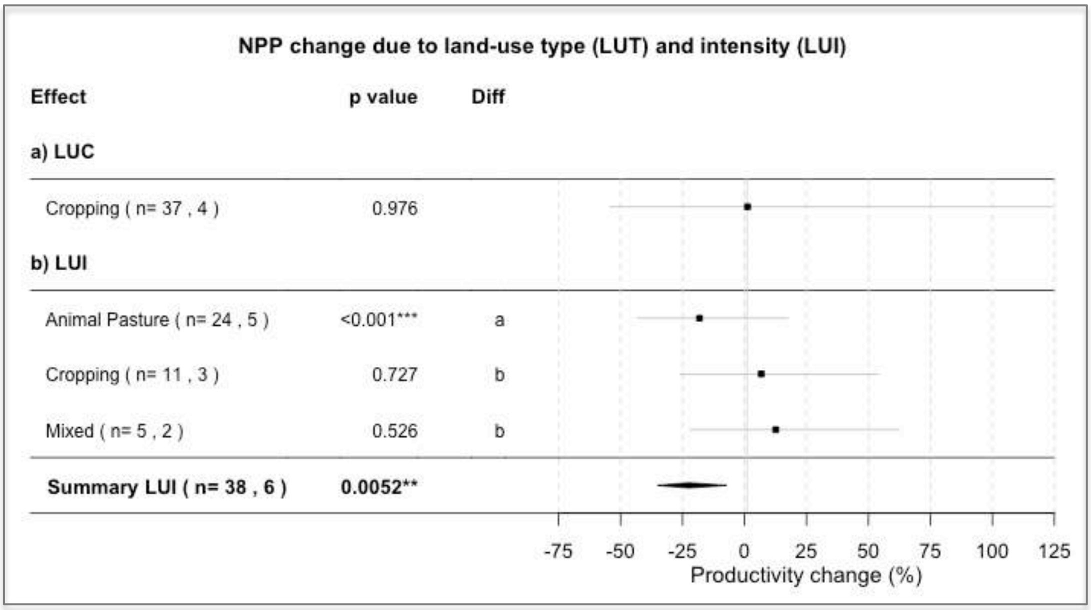

Fig. 4.8: Percent in productivity changes (+/- 95%-CI) due to different land-use activities in datasets. a) Land-use type (LUT) and b) Land-use intensity (LUI) (n: number of observations, significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-), Diff: different letters indicating pairwise comparisons that are significant and *P*<0.05). Summary (average effect +/- 95%-CI) represented as a rhombus.

Ecosystem

The effects of land-use type on productivity were positive in grassland and negative in forest and mixed ecosystems, with a large variance between citations (Fig. 4.9a). The effects of land-use intensity on productivity were negative for all ecosystems, but significant only for shrubland, which may seem unusual given that they are not significantly different between them, but can happen in unusual statistical circumstances (Fig. 4.9b).

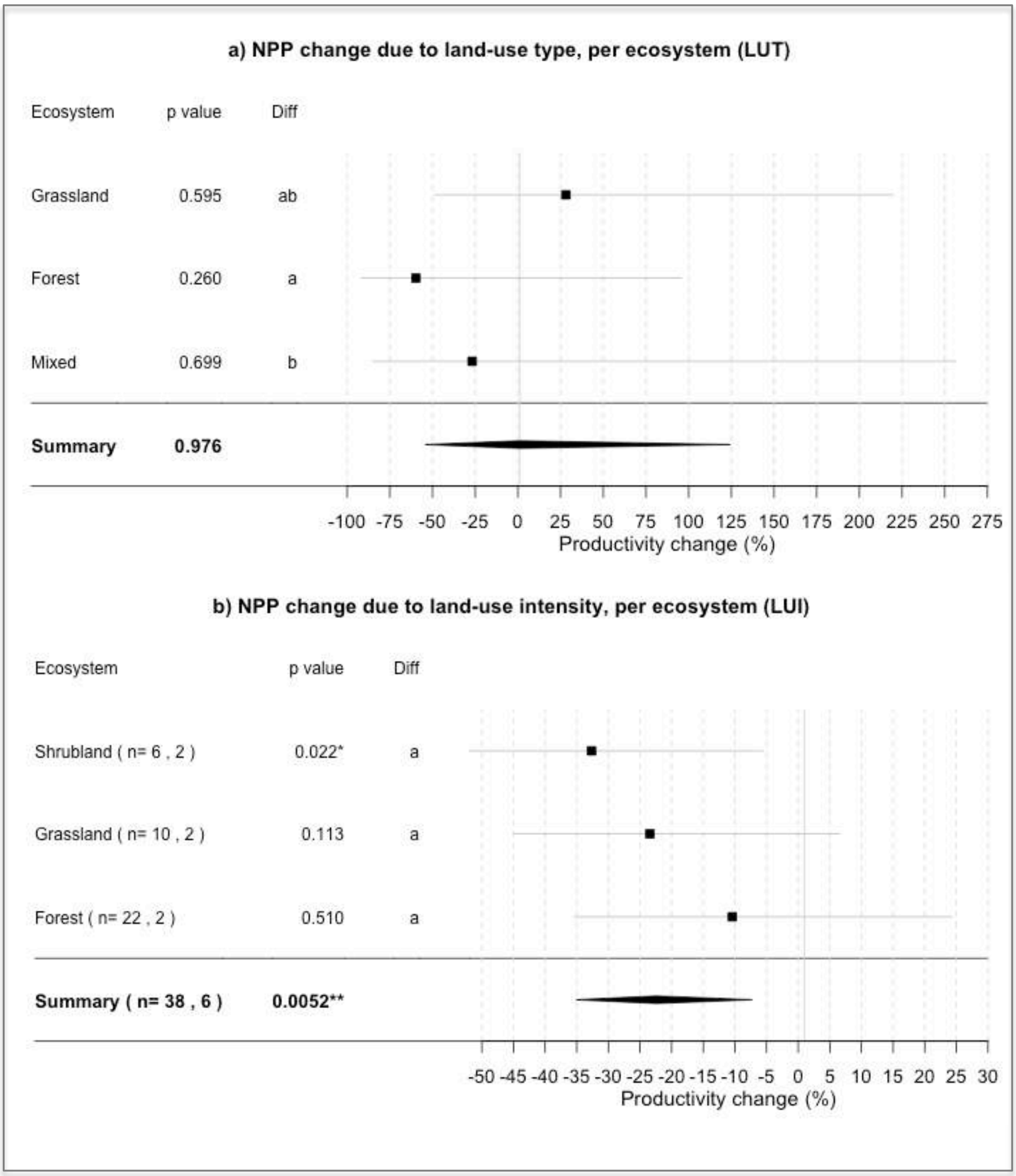

Fig. 4.9: Percent in productivity changes (+/- 95% CI) due to different land-use activities per ecosystem, in datasets. a) Land-use type (LUT) and b) Land-use intensity (LUI). n: number of observations, significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-), Diff: different letters indicating pairwise comparisons that are significant and *P*<0.05). Summary (average effect +/- 95% CI) represented as a rhombus.

b.3) Biodiversity effects on productivity

Out of 5215 papers, 51 were read (for a matter of time) and 7 were selected; some of them with several independent effects, to an overall total of 29 effects reported. In this dataset biodiversity showed a large, positive effect on productivity (log response ratio: 0.4551, se: 0.1166, *P*<0.001); when back-transformed with the exponential function this can be interpreted as a 57.63% (95%-CI 25.42%, 98.12%) increase in productivity due to biodiversity. No evidence of publication bias was found for the dataset on land-use type, using funnel plots, fail-safe n, and Egger tests (Fig 4.S1.1, Table 4.S2.1 (Suppl. Material)).

We used the following modifiers in meta-regressions: initial number of species (control) and presence of different functional groups (legume, forbs, grasses, herbs) (treatment). Table 4.5 shows the results of a sequential ANOVA, in which presence of legumes and forbs were significant. Note that inverting the order in which the functional groups were fitted (from herbs to legumes), still gave significant only for legumes (LRT: 15.12, P<0.001***) and forbs (LRT: 7.81, P:0.005**)

Table 4.5: Anova-type tests for multivariate meta-analysis with sequentially added modifiers (for the relationship between biodiversity and productivity, BD-NPP) (LTR: Log likelihood ratio from full/reduced model, df: degrees of freedom), significance codes for *P*-values: *P*<0.001 (***), *P*<0.01 (**), *P*<0.05 (*), *P*>=0.05 (-).

Term added to the model	df	LRT	p-value
Initial Biodiversity Level	1	2.8881	0.0892
Presence of Legumes	1	5.6504	0.0175**
Presence of Forbs	1	9.2276	0.0024***
Presence of Shrubs	1	0.4297	0.5121
Presence of Herbs	1	0.9102	0.3401

Meta-regressions for effects of different modifiers on effects of biodiversity on productivity

Initial species richness

We performed a meta-regression using the initial number of species (which is the species richness in the control) as modifier and confirmed that it did not explain significant heterogeneity in effects on its own (0.021, CI (-0.034, 0.076), ns) (only three observations that started with numbers higher than four species) (Fig. 4.S1.2).

Presence of functional groups

We performed a meta-regression with the presence/absence of each of the functional groups in the initial mix of species, separately (testing presence/absence of each), where only presence of legumes and forbs were significant (Figure 4.10).

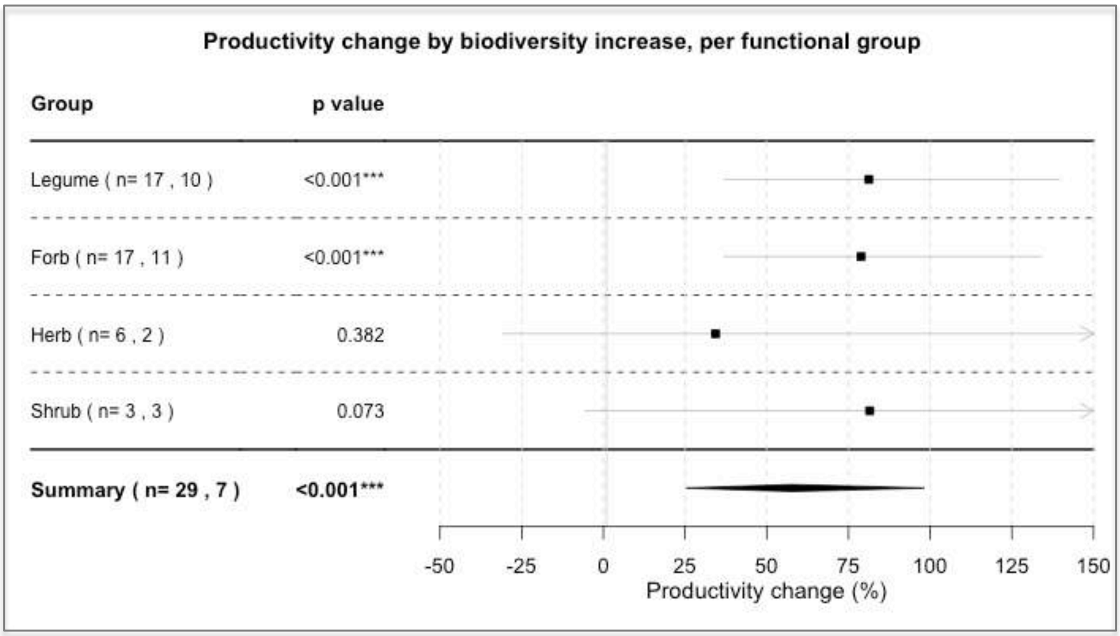

Fig. 4.10: Percent in productivity changes with biodiversity increase, per functional group (Average +/- 95%-CI). n: number of observations, significance codes for *P*-values: $P<0.001$ (***), $P<0.01$ (**), $P<0.05$ (*), $P>=0.05$ (-), Diff: different letters indicating pairwise comparisons that are significant and $P<0.05$). Summary (average effect +/- 95% CI) represented as a rhombus.

b.4) Land-use alteration (LUA) effects on nutritional status

We found 796 papers, of which only 7 contained quantitative information on nutritional status changes following land-use alteration (from no activity in a modified landscape to an activity that increases both biodiversity and productivity at the same time). A total of 15 independent effects were identified, most of them on house gardens, in rural areas of low-income countries. Studies included land-use changes to increase productivity in a sustainable way, transformations to agroecology and increases in biodiversity; there were no records for impacts of intensity or traditional agriculture on nutritional status. In this dataset, the average effect was large and positive though not statistically significant (log response ratio: 0.3546, se: 0.1743, $P>0.05$); when back-transformed with the exponential function this can be interpreted as a 142.56% (CI 119.76, 169.71) increase in productivity due to biodiversity. Given the small dataset available, there is naturally evidence of publication bias according to the funnel plot, which is relatively asymmetric, fail-safe n (low), and Egger tests (large intercept) (Fig 4.S1.1, Table 4.S2.1).

Both productivity and biodiversity increased in the land-use changes described in these land-use alterations, and the effects were not reported independently. Therefore, it was not possible to disentangle the effects of each, for example, using productivity and biodiversity levels as modifiers.

A model with type of intervention and nutritional index showed that only the first could explain significantly part of the heterogeneity between studies; the type of index used did not significantly explain heterogeneity (Table 4.6). We explored each modifier independently through meta-regressions. Note that the models work with low number of effects (even 1) because each of them has a sampling variance (error of replications within studies).

Table 4.6: Anova-type tests for multivariate meta-analysis with sequentially added modifiers (for the relationship between land-use alteration and nutritional status, LUA-NUT). (LTR: Log likelihood ratio from full/reduced model, df: degrees of freedom)

Term added to the model	df	LRT	p-value
Index	6	30.4796	<0.001
Type of intervention	3	3.4425	0.3283

Meta-regressions for effects of different modifiers on effects of land-use alteration on nutritional status

Nutritional status Index

We performed a meta-regression with the type of index used to measure nutrient status. The land-use interventions show positive effects in nutritional status regardless of the index used, but some showed larger variance than others (particularly self-reported health, although note the low number of observations) (Fig. 4.11).

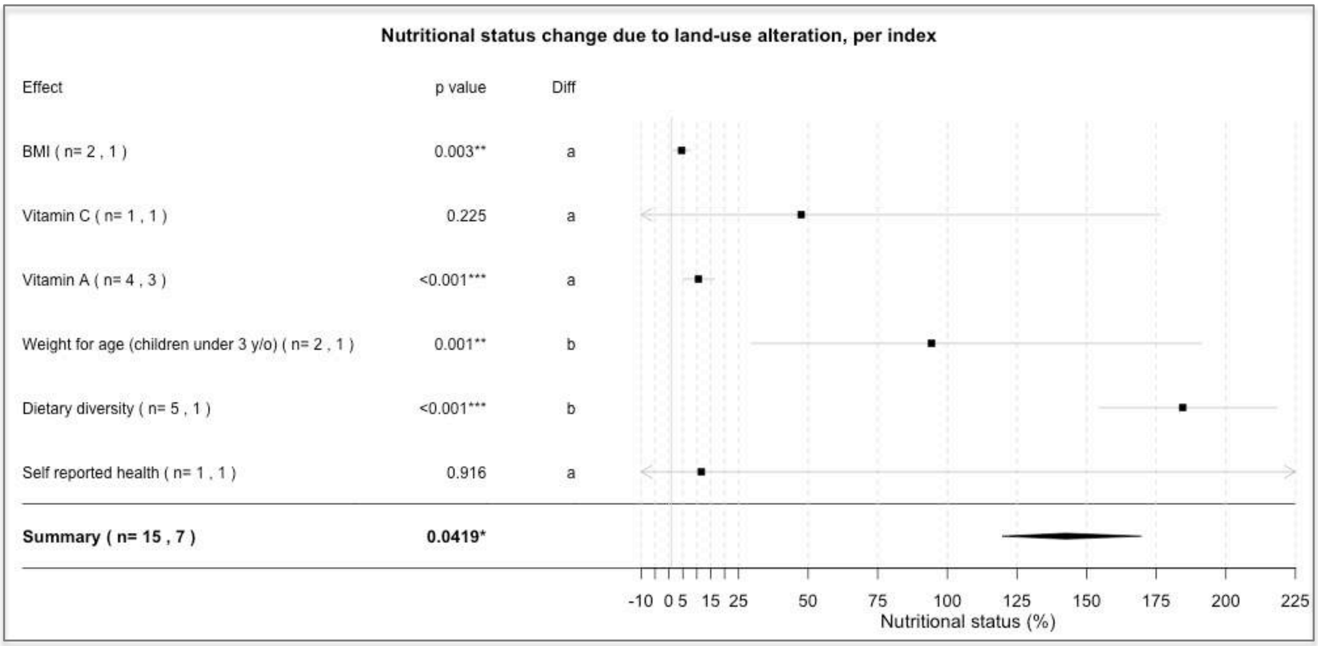

Fig. 4.11: Percent in nutritional status changes (+/- 95%-CI), per index. (n: number of observations, p-value significant codes 0.001(***), 0.01(**), 0.05 (*), ns: non-significant, n: number of studies, observations, Diff: pairwise comparisons. Summary (average effect +/- 95%-CI) represented as a rhombus).

Type of Intervention

We performed meta-regressions with the type of interventions (Figure 4.12). All interventions had a positive effect in increasing the nutritional status (increase nutrient consumption, better health). Using compost, increasing the size of the farm, crop diversity and the use of legumes showed the largest positive effects.

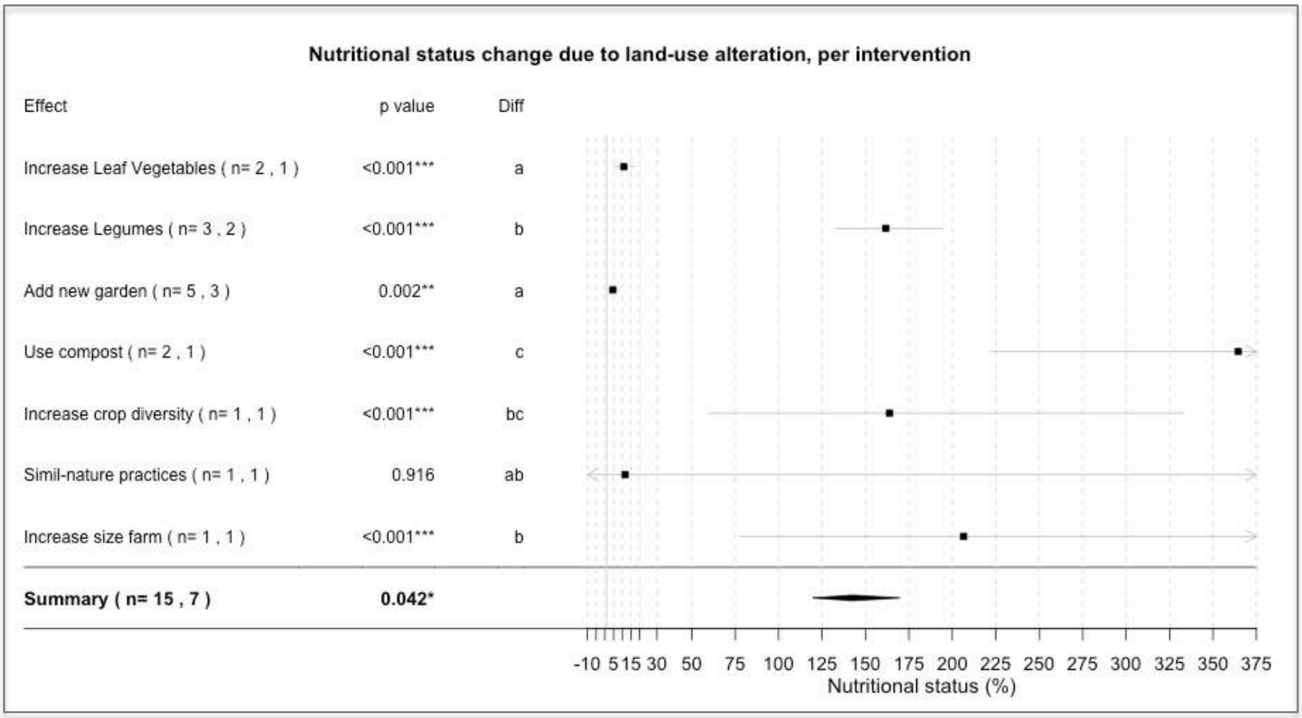

Fig. 4.12: Percent in nutritional status changes (+/- 95%-CI), per type of land-use intervention (Average +/ SE). (n: number of observations, p-value significant codes 0.001(***), 0.01(**), 0.05 (*), ns: non-significant, n: number of studies, observations, Diff: pairwise comparisons. Summary (average effect +/- 95%-CI) represented as a rhombus.

Semi-quantitative and qualitative analyses from studies not used in meta-analysis

Some of the studies that were not used in the meta-analysis contained useful conceptual frameworks, conclusions or qualitative reviews (full list in Table 4.S2.2). Summary data for this set of studies are shown in Fig. 4.13, and the top 10 conclusions across studies are listed in Table 4.7.

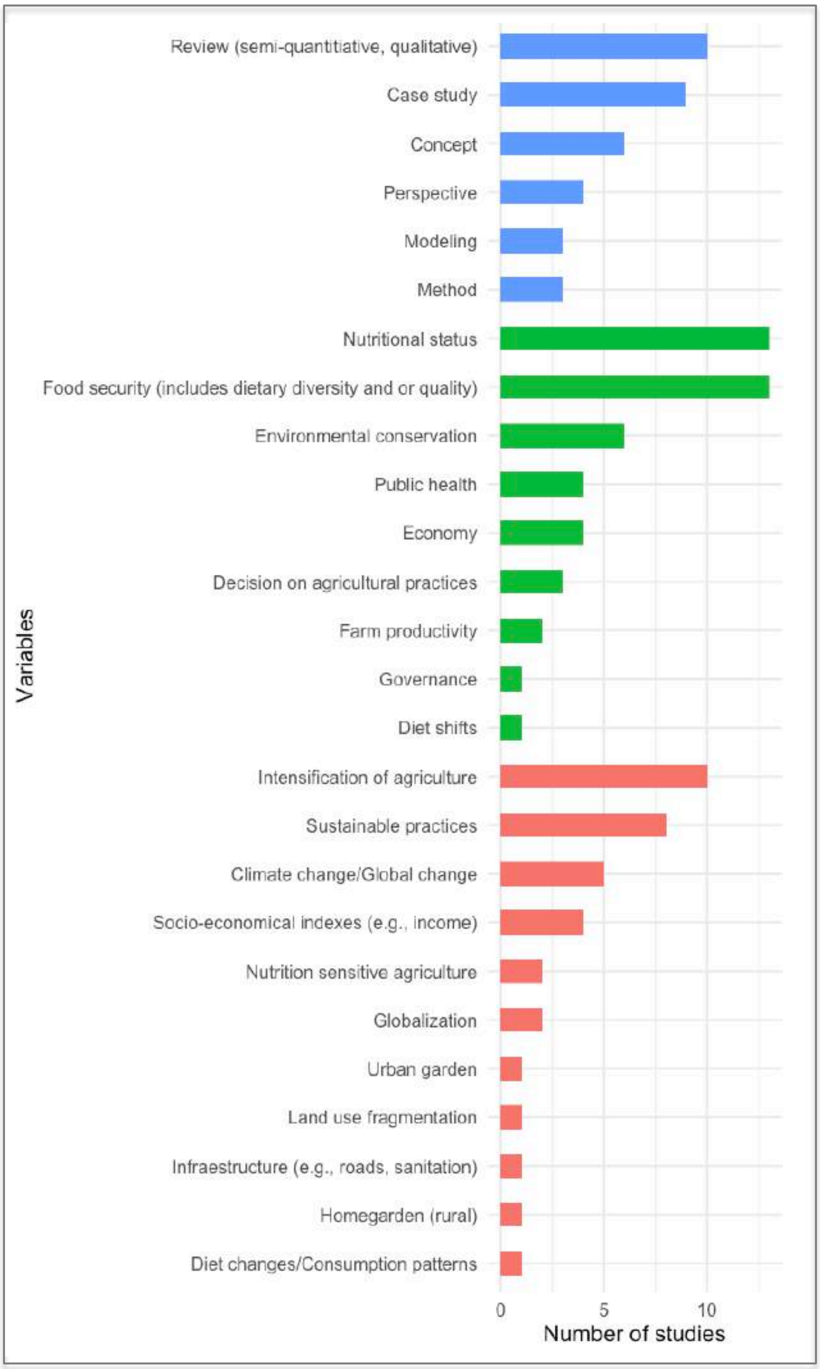

Fig. 4.13: Summary from non-quantitative studies. Grouped by type of study (blue), response variables of nutritional status indexes or food security (green) and variables used as effect variables (global change drivers) (red).

Table 4.7: Top 10 conclusions from studies not used for quantitative analysis

	Summary conclusions
1) Systemic analyses	System analyses that take into account multiple factors (economic, social and environmental) and account for indirect effects are more representative of reality and useful than single factor studies.
2) Policies	Few policies currently in place to increase nutritional status of a population 1) measure the direct outcome, 2) have been tested for efficiency, 3) support diversification of produce other than stable crops.
3) Research gaps	There are research gaps in all variables of interest in this system, particularly at local scales, where lack of data and proper experimental designs are pervasive.
4) Intensity vs. redistribution	There is relatively large support for the fact that current production in agriculture theoretically fits current nutritional demands (and possibly those of the population expected in 2050), in terms of biomass, nutrient content and energy production (biofuels).
5) Scale	Large scale studies using nationwide and international data are not sufficient to understand observed outcomes of interventions: specific trajectories and tradeoffs occur at local scale, and sometimes differ largely even between farms of the same location and cultural background.
6) Use of proxies	Many counterintuitive outcomes have been observed such as: 1) Increasing farm production does not always lead to greater financial income. 2) Having a large availability of nutrient-rich foods does not always lead to greater consumption or better nutritional status. 3) Ingestion of nutrients is not equal to assimilation.
7) Confounding effects	Climate, soil properties, seasonality of crops, wealth status, education in nutrition, and gender issues should be considered together with the implementation of land-use changes aimed at increasing biodiversity and productivity.
8) Trends	Nutrition sensitive agricultural programs have the potential to reduce environmental impacts while increasing nutritional status of the population. However, the trend toward intensified land-use is in the opposite direction.
9) Cost of sustainability	Sustainable practices in farms, such as increasing biodiversity, are costly and may not be profitable without governmental income support.
10) Terminology	The terminology used in studies is sometimes ambiguous and confusing, hindering data synthesis.

b.5) Diet-change effects on land-use activities

We did not find studies linking a change in nutritional status of a community with land-use changes in that direction, but we found several studies that link shifts in diets (a proxy of nutrition) with land-use change (Table 4.S2.3). The top conclusions are shown in Table 4.8. Shifts in diets are associated usually with changes in the nutritional status (Fan et al., 2019), therefore we explored this relationship. Most papers report a change from plant- to animal-based diets and associated positive impacts on ecological factors (e.g., reduced need of land-use change, reduced fertilizers, reduced energy input). Too few of the papers contained quantitative data for meta-analysis.

Table 4.8: Top 5 conclusions from studies not used for quantitative analysis

Summary conclusions	
1) Problematic definition of a "healthier diet"	The definition of healthier diets is different across countries, and therefore studies addressing the impact of shifts to "healthier diets" without quantitatively describing the contents, are not directly comparable.
2) Increase in land-use intensive products	Some healthier diets increase meat, fruit and dairy consumption, which in turn requires more land space and so increases environmental impact.
3) Systemic analyses	Because they are tightly related, land-use, carbon emissions, fertilizer input, and water use should all be assessed together and not separately.
4) Definitions for types of practices	Sustainable practices, seasonal diets, locally-grown produce, outdoor grown produce: these terms should be defined quantitatively according to the study so that they are comparable to others.
5) Wealth and economy	Currently there would not be enough land to satisfy the demand of the whole population of the Earth if they would switch to an affluent diet, in most countries in which this was studied.

4.5 Conclusions

General conclusions

We were interested in describing the strength of the causal relationships between land-use change, biodiversity levels, productivity levels and nutritional status of human populations. We performed an exploratory study to link these four variables that are theoretically and in environmental policies tightly linked, but that seldom have been considered together in experimental or observational studies. We broadly defined the variables of interest to encompass larger sections of the literature, in order to look for patterns and trends in the responses, and to further understand the possible feedbacks in the system. Figure 4.14 shows the summary of all quantitative relationships studied in the thesis.

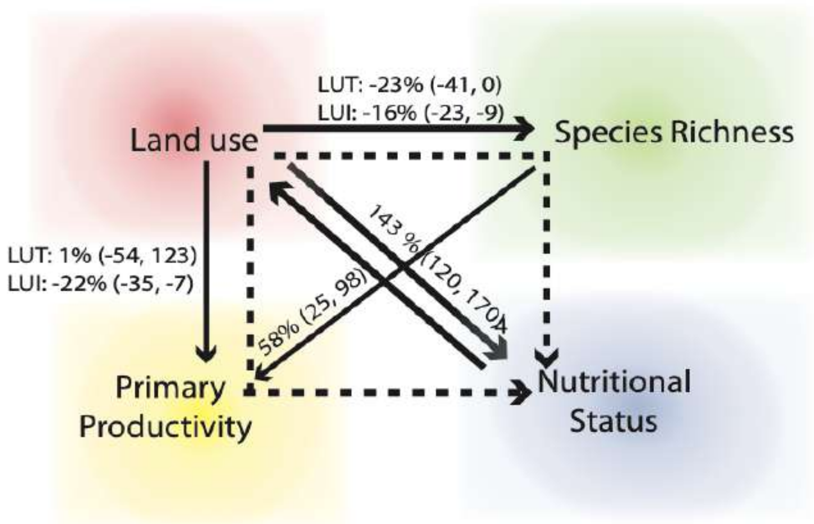

Fig. 4.14: Summary from relationships studied quantitatively, following Fig 4.2b, with average effect sizes (+/- 95% CIs).

By performing a broad literature search we expected to find studies reporting on all of the possible relationships for the system of interest (Fig. 4.2). We found sufficient data to report on five out of the sixteen possible relationships (quantitatively on four) (Fig.4.14). Each interaction was complex to analyze by itself, with multiple modifiers and levels, which probably explains why, to our knowledge, there are no other studies considering all of them simultaneously. It is possible that with an exhaustive literature search the rest of the relationships could be also explored. For the relationships that we could analyze we found some interesting outcomes that possibly would have been missed with independent studies.

Subject specific conclusions

Land-use change and intensity lead to major biodiversity losses, consistent with the existing literature that identifies land use as a major global change, although the effects were not equal in all ecosystems and for all taxa affected. Animal pasture was the land-use change with the largest negative effects on biodiversity and on productivity. We know from the literature that grazing can be managed to benefit biodiversity (Rook & Tallowin, 2003). None of the papers included in our analyses mentioned biodiversity enhancement as a goal, but all of them used animals in the way productive grazing for commercialization use them. Hence, results suggest that unless biodiversity management is included as a goal in parallel to animal production for commercialization, it is not always the case that this will naturally occur. This is in line with other studies that make specific recommendations on how to use grazing to this end, tailored to the taxa that are the target of conservation (Rook et al., 2004).

Invertebrates were the most affected by land-use change, but other taxa were equally affected by land-use intensity. This is consistent with recent studies that found strong insect declines due to land use (Seibold et al., 2019). Invertebrates are usually considered good bioindicators of land-use changes in a variety of situations (Andersen & Majer, 2004) and our results support this claim. Mixed activities (agroforestry or mixed with human settlements) had negative impact on biodiversity but milder than each land-use type independently. It is known that the impact of different land-use types is not only one of the activities being carried out per se, but also the preparation that the land requires for them (e.g., tilling before crops) (McLaughlin & Mineau, 1995). It is possible that by mixing different types of activities, the impact is distributed among affected species or different niches are created to accommodate more species. This would have to be studied further, with a more diverse dataset.

Regarding productivity, land-use type showed a slightly positive effect and land-use intensity a large negative one on productivity. A recent review on causes of changes in net primary productivity suggests large discrepancies in reports, mainly due to field collections of data not being standardized and missing information in reports (Šímová & Storch, 2017). Our results are in line with this review, given the large heterogeneity in results, even in similar regions and land-use types. The advantage of meta-analysis as used here is that this variation among studies and citations can be quantified and removed from the estimation of overall effects. To our knowledge, there are no other meta-analyses or reviews summarizing literature on how land-use type and intensity change net primary productivity globally, so we cannot compare our results with previous work. A study using a globally extensive experiment (NutNet) generalized conclusions from their study to "how grasslands would respond to environmental change", including changes in primary productivity, although their focus was on biodiversity–productivity relationships and not on the driver of change (e.g., nutrient input) (Borer et al., 2017). They concluded that biodiversity is promoting and maintaining productivity, and hence biodiversity declines would imply a direct negative effect on such productivity. In our study, biodiversity showed indeed a large positive effect on productivity (more than 50%). This would be consistent with NutNet studies and others reporting productivity losses due to loss in biodiversity. It would be interesting to expand our meta-analysis to integrate more than one relationship in a type of meta-path-analysis or meta-structural-equation model (meta-SEM). However, we did not do this here because it is not clear how the different data sources for each relationship would affect the analysis. Ideally, one would have to find at least some individual studies that looked at more than one relationship, for example land use → species richness → primary productivity and land use → primary productivity (Fig 4.14)

Our results suggest a stark increase in productivity following an increase in biodiversity as a treatment. Despite controversies on the mechanisms underlying this relationship, there seems to be consensus in this direction (Balvanera et al., 2006; Cardinale et al., 2007; Duffy et al., 2017; Isbell et al., 2011; Oehri et al., 2017). This increase could be explained by species richness per se, but in our case the effect was underpinned by the presence of particular plant functional groups, namely forbs and legumes, in mixed-species plant communities. The role of legumes driving productivity increases in plant mixtures has been a focus of many grassland biodiversity experiments (Fargione et al., 2007; Roscher et al., 2013) and it is interesting that we could pick up on this result with our study design and relatively few studies with high variability. However, positive effects of species richness on productivity are also commonly observed in the absence of legumes (e.g., (Van Ruijven & Berendse, 2003) and our further findings of biodiversity an presence of forb effects is consistent this.

The major increase observed in productivity with an increase in biodiversity and in nutritional status with an intervention in land use are consistent in direction but not in magnitude with the literature available on the subject (Masset et al., 2012). Studies that looked into the species richness–productivity relationship were mostly performed in grassland ecosystems, with a pool of lowland angiosperms and in the northern hemisphere. Increasing the diversity of settings in biodiversity–productivity studies would increase the level of representativity. In a similar way, studies linking biodiversity and productivity to nutritional status were all performed in low-income countries of the southern hemisphere (and some in Asia). Micronutrient deficiencies are common also in wealthy countries (Díaz et al., 2003), and by not analyzing the impact that land-use changes possibly have on them, we may be missing valuable information on the mechanisms underlying this interaction. There is consensus on the urgency of establishing links between land-use changes and nutritional status (and health in general) (Simopoulos et al., 2013). From our review, it seems to be difficult to measure direct impacts on nutritional status, even when there are interventions on land-use change directed to this aim.

Challenges to integration

One of the difficulties we faced in all the meta-analyses was the loose definition of key terms in studies. For example, the definition of agroecology as a "set of farming practices that attempt to mimic natural systems" (Nyantakyi-Frimpong et al., 2017), without a list of specific measures describing it, makes it difficult to know which other studies can be pooled together with it. Biome definitions, land-use practices and intensity of interventions were the areas in which this challenge was mostly felt. We call for researchers in disciplines that deal with these terms and concepts to look further for commonalities and standard indexes that can be reported, if not uniquely, at least together with self-defined categories, towards contributing to future global data syntheses. This problem is typical for the ecological and environmental sciences compared with for example clinical trials. Nevertheless, it is possible to use meta-analysis on such heterogeneous data, as we have shown here and others have shown in previous studies, e.g. calculating responses across vastly different ranges of nutrient additions, treating them all the same simply as nutrient additions (see e.g. Hooper et al. 2012, Yuan et al. 2017). So far only in few cases could meta-analyses use specific values of treatment variables, e.g. actual species richness values (e.g. Balvanera et al. 2006), allowing them to calculate correlations instead of response ratios to measure effects.

Furthermore, we found a large number of reports on the effects of interventions, for example, land-use interventions effects on nutritional status of communities, many of them even include average effects (e.g., Percent of stunted children declined in 51%), but they do so with no errors or number of observations associated with those averages. Although these reports are relevant for the description of project outcomes, they cannot be used for quantitative analyses with current meta-analysis tools, in comparison with other projects. This means that interesting patterns and ideas of modifiers that may explain the known heterogeneity between results get lost (and definitely do when in absence of errors and number of observations is accompanied by lack of access to raw data). This is also the case of studies with low or no variance in the results that cannot be used due to caveats in current tools used for meta-analysis which cannot deal with them (e.g., metafor R package used in this thesis).

General recommendations

Although it provided some valuable insights and experience in data management and analysis, there are some issues with the design that could be improved. It would be necessary to get larger sample sizes, better information about explanatory variables and responses and more sophisticated analysis tools to progress. Furthermore, one could ask for better designs and reporting standards of individual studies. One interesting further step in analysis would be to integrate the separate meta-analyses done here into meta-SEMs (path analyses) (e.g., (Grace et al., 2007)). Another goal would be to have continuous effects variables of modifiers to make more quantitative predictions.

Overall, the integration of data across disciplines in a network has the potential to show hidden patterns that are not visible with isolates studies. Furthermore, by doing several rounds of bibliography search and feeding back into the design, it may be possible to reach a thorough understanding of the literature, current research gaps and develop new working hypotheses. We call for more collaboration in interdisciplinary projects, use of standard indexes, narrowing of definitions for practical use and data sharing, towards a better understanding of global change systems.

Data availability

The databases with means, errors and effect sizes, as well as entries for all modifiers can be found in KNB public repository online, together with its associated metadata. The basic R code script used for the analysis can be found in M.A.P. Github account (https://github.com/mparre).

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Authors' contributions

M.A.P. selected the variables of interest, performed the literature search, extracted data, built databases, analyzed the data and wrote manuscript. V.M participated in the initial development of the idea of a network of meta-analysis across disciplines. B.S. and P.B. participated in and supervised the analysis of the data. B.S., O.L.P., N.B., and M.E.S. designed and developed the original idea of an integration data project. O.L.P. acted as main supervisor during the development of the project.

4.6 References

Allen, T., Prosperi, P., Cogill, B., & Flichman, G. (2014). Agricultural biodiversity, social–ecological systems and sustainable diets. *Proceedings of the Nutrition Society*, *73*(4), 498–508. Cambridge Core. https://doi.org/10.1017/S002966511400069X

Andersen, A. N., & Majer, J. D. (2004). Ants Show the Way Down Under: Invertebrates as Bioindicators in Land Management. *Frontiers in Ecology and the Environment*, *2*(6), 291–298. JSTOR. https://doi.org/10.2307/3868404

Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J.-S., Nakashizuka, T., Raffaelli, D., & Schmid, B. (2006). Quantifying the evidence for biodiversity effects on ecosystem functioning and services: Biodiversity and ecosystem functioning/services. *Ecology Letters*, *9*(10), 1146–1156. https://doi.org/10.1111/j.1461-0248.2006.00963.x

Blüthgen, N., & Klein, A.-M. (2011). Functional complementarity and specialisation: The role of biodiversity in plant–pollinator interactions. *Basic and Applied Ecology*, *12*(4), 282–291. https://doi.org/10.1016/j.baae.2010.11.001

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). Meta-Regression. In *Introduction to Meta-Analysis* (pp. 187–203). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470743386.ch20

Borer, E. T., Grace, J. B., Harpole, W. S., MacDougall, A. S., & Seabloom, E. W. (2017). A decade of insights into grassland ecosystem responses to global environmental change. *Nature Ecology &Amp; Evolution*, *1*, 0118.

Bretz, F., Hothorn, T., & Westfall, P. (2010). *Multiple comparisons using R* (1st ed.). Chapman and Hall/CRC.

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S., & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature*, *486*(7401), 59–67. https://doi.org/10.1038/nature11148

Cardinale, B. J., Wright, J. P., Cadotte, M. W., Carroll, I. T., Hector, A., Srivastava, D. S., Loreau, M., & Weis, J. J. (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proceedings of the National Academy of Sciences*, *104*(46), 18123–18128.

CBD. (2010, October 18). Decision X/2. *Convention on Biological Diversity*. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets, Nagoya, Japan.

Chakona, G., & Shackleton, C. M. (2018). Household Food Insecurity along an Agro-Ecological Gradient Influences Children's Nutritional Status in South Africa. *Frontiers in Nutrition*, *4*, 72. https://doi.org/10.3389/fnut.2017.00072

Chapin, & Eviner, V. T. (2007). 8.06—Biogeochemistry of Terrestrial Net Primary Production. In H. D. Holland & K. K. Turekian (Eds.), *Treatise on Geochemistry* (pp. 1–35). Pergamon. https://doi.org/10.1016/B0-08-043751-6/08130-5

Chapin, Randerson, J., McGuire, A., Foley, J., & Field, C. (2008). Changing feedbacks in the climate–biosphere system. *Frontiers in Ecology and the Environment*, *6*(6), 313–320. https://doi.org/10.1890/080005

Cunningham, K., Ploubidis, G. B., Menon, P., Ruel, M., Kadiyala, S., Uauy, R., & Ferguson, E. (2015). Women's empowerment in agriculture and child nutritional status in rural Nepal. *Public Health Nutrition*, *18*(17), 3134–3145. Cambridge Core. https://doi.org/10.1017/S1368980015000683

Díaz, J. R., Cagigas, A. de las, & Rodríguez, R. (2003). Micronutrient deficiencies in developing and affluent countries. *European Journal of Clinical Nutrition*, *57*(1), S70–S72. https://doi.org/10.1038/sj.ejcn.1601820

Duffy, J. E., Godwin, C. M., & Cardinale, B. J. (2017). Biodiversity effects in the wild are common and as strong as key drivers of productivity. *Nature*, *549*(7671), 261–264.

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ*, *315*. https://doi.org/10.1136/bmj.315.7109.629

Fan, S., Yosef, S., & Pandya-Lorch, R. (2019). *Agriculture for improved nutrition: Seizing the momentum*. CABI.

Fargione, J., Tilman, D., Dybzinski, R., Lambers, J. H. R., Clark, C., Harpole, W. S., Knops, J. M. H., Reich, P. B., & Loreau, M. (2007). From Selection to Complementarity: Shifts in the Causes of Biodiversity-Productivity Relationships in a Long-Term Biodiversity Experiment. *Proceedings: Biological Sciences*, *274*(1611), 871–876.

Fleuret, P., & Fleuret, A. (1980). Nutrition, Consumption, and Agricultural Change. *Human Organization*, *39*(3), 250–260. JSTOR.

Flynn, D. F. B., Mirotchnick, N., Jain, M., Palmer, M. I., & Naeem, S. (2011). Functional and phylogenetic diversity as predictors of biodiversity–ecosystem-function relationships. *Ecology*, *92*(8), 1573–1581. https://doi.org/10.1890/10-1245.1

Godfray, H. C. J., & Garnett, T. (2014). *Food security and sustainable intensification*. *369*(1639). https://doi.org/10.1098/rstb.2012.0273

Gordon, M., & Lumley, T. (2019). *Package "forestplot"—Advanced Forest Plot Using "grid" Graphics* (Version 1.9) [Computer software]. https://cran.r-project.org/web/packages/forestplot/forestplot.pdf

Grace, J. B., Michael Anderson, T., Smith, M. D., Seabloom, E., Andelman, S. J., Meche, G., Weiher, E., Allain, L. K., Jutila, H., Sankaran, M., Knops, J., Ritchie, M., & Willig, M. R. (2007). Does species diversity limit productivity in natural grassland communities? *Ecology Letters*, *10*(8), 680–689. https://doi.org/10.1111/j.1461-0248.2007.01058.x

Hammond, R. A., & Dubé, L. (2012). A systems science perspective and transdisciplinary models for food and nutrition security. *Proceedings of the National Academy of Sciences*, *109*(31), 12356. https://doi.org/10.1073/pnas.0913003109

Hector, A., & Bagchi, R. (2007). Biodiversity and ecosystem multifunctionality. *Nature*, *448*(7150), 188–190. https://doi.org/10.1038/nature05947

Hooper, D. U., Adair, E. C., Cardinale, B. J., Byrnes, J. E. K., Hungate, B. A., Matulich, K. L., Gonzalez, A., Duffy, J. E., Gamfeldt, L., & O'Connor, M. I. (2012). A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature*, *486*, 105–108. https://doi.org/10.1038/nature11118

Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W. S., Reich, P. B., Scherer-Lorenzen, M., Schmid, B., Tilman, D., van Ruijven, J., Weigelt, A., Wilsey, B. J., Zavaleta, E. S., & Loreau, M. (2011). High plant diversity is needed to maintain ecosystem services. *Nature*, *477*(7363), 199–202. https://doi.org/10.1038/nature10282

Jax, K., & Setälä, H. (2005). Function and "Functioning" in Ecology: What Does It Mean? *Oikos*, *111*(3), 641–648. JSTOR.

Koricheva, J., & Gurevitch, J. (2014). Uses and misuses of meta-analysis in plant ecology. *J Ecol*, *102*. https://doi.org/10.1111/1365-2745.12224

Koricheva, J., Jennions, M. D., & Lau, J. (2013). Temporal trends in effect sizes: Causes, detection and implications. In J. Koricheva & J. Gurevitch (Eds.), *Mengersen K, editors*. Princeton University Press.

Kremen, C., & Ostfeld, R. S. (2005). A call to ecologists: Measuring, analyzing, and managing ecosystem services. *Frontiers in Ecology and the Environment*, *3*(10), 540–548. https://doi.org/10.1890/1540-9295(2005)003[0540:ACTEMA]2.0.CO;2

Lajeunesse, M. J. (2015). Bias and correction for the log response ratio in ecological meta-analysis. *Ecology*, *96*(8), 2056–2063. https://doi.org/10.1890/14-2402.1

Laland, K. N., & Boogert, N. J. (2010). Niche construction, co-evolution and biodiversity. *Special Section: Coevolutionary Ecological Economics: Theory and Applications*, *69*(4), 731–736. https://doi.org/10.1016/j.ecolecon.2008.11.014

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, *108*(9), 3465–3472. https://doi.org/10.1073/pnas.1100480108

Lefcheck, J. S., Byrnes, J. E. K., Isbell, F., Gamfeldt, L., Griffin, J. N., Eisenhauer, N., Hensel, M. J. S., Hector, A., Cardinale, B. J., & Duffy, J. E. (2015). Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. *Nat Commun*, *6*. http://dx.doi.org/10.1038/ncomms7936

Leng, G., & Huang, M. (2017). Crop yield response to climate change varies with crop spatial distribution pattern. *Scientific Reports*, *7*(1), 1463. https://doi.org/10.1038/s41598-017-01599-2

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., & Li, S. (2015). Systems integration for global sustainability. *Science*, *347*(6225). https://doi.org/10.1126/science.1258832

Luther, D., Hilty, J., Weiss, J., Cornwall, C., Wipf, M., & Ballard, G. (2008). Assessing the impact of local habitat variables and landscape context on riparian birds in agricultural, urbanized, and native landscapes. *Biodiversity and Conservation*, *17*(8), 1923–1935. https://doi.org/10.1007/s10531-008-9332-5

Maluf, R. S., Burlandy, L., Santarelli, M., Schottz, V., & Speranza, J. S. (2015). Nutrition-sensitive agriculture and the promotion of food and nutrition sovereignty and security in Brazil. *CiÃ\textordfemeninencia & SaÃºde Coletiva*, *20*, 2303–2312.

Manning, P., van der Plas, F., Soliveres, S., Allan, E., Maestre, F. T., Mace, G., Whittingham, M. J., & Fischer, M. (2018). Redefining ecosystem multifunctionality. *Nature Ecology & Evolution*, *2*(3), 427–436. https://doi.org/10.1038/s41559-017-0461-7

Masset, E., Haddad, L., Cornelius, A., & Isaza-Castro, J. (2012). Effectiveness of agricultural interventions that aim to improve nutritional status of children: Systematic review. *BMJ*, *344*, d8222. https://doi.org/10.1136/bmj.d8222

McLaughlin, A., & Mineau, P. (1995). The impact of agricultural practices on biodiversity. *Agriculture, Ecosystems & Environment*, *55*(3), 201–212. https://doi.org/10.1016/0167-8809(95)00609-V

MEA. (2005). *Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf

Mittelbach, G. G., Steiner, C. F., Scheiner, S. M., Gross, K. L., Reynolds, H. L., Waide, R. B., Willig, M. R., Dodson, S. I., & Gough, L. (2001). What is the observed relationship between species richness and productivity? *Ecology*, *82*(9), 2381–2396. https://doi.org/10.1890/0012-9658(2001)082[2381:WITORB]2.0.CO;2

Mohsena, M., Hossain, M., Chakraborty, B., Bayes, A., & Rahman, A. N. M. (2018). Fragile environment, seasonality and maternal and childhood undernutrition in Bangladesh. *Journal of Biosocial Science*, *50*(5), 579–603. Cambridge Core. https://doi.org/10.1017/S002193201700044X

Nyantakyi-Frimpong, H., Kangmennaang, J., Bezner Kerr, R., Luginaah, I., Dakishoni, L., Lupafya, E., Shumba, L., & Katundu, M. (2017). Agroecology and healthy food systems in semi-humid tropical Africa: Participatory research with vulnerable farming households in Malawi. *Ecohealth: An African Perspective*, *175*, 42–49. https://doi.org/10.1016/j.actatropica.2016.10.022

Oehri, J., Schmid, B., Schaepman-Strub, G., & Niklaus, P. A. (2017). Biodiversity promotes primary productivity and growing season lengthening at the landscape scale. *Proceedings of the National Academy of Sciences*, *114*(38), 10160–10165. https://doi.org/10.1073/pnas.1703928114

Paquette, A., & Messier, C. (2011). The effect of biodiversity on tree productivity: From temperate to boreal forests: The effect of biodiversity on the productivity. *Global Ecology and Biogeography*, *20*(1), 170–180. https://doi.org/10.1111/j.1466-8238.2010.00592.x

Parreño, M. A., Schmid, B., & Petchey, O. (in preparation). *Identification, comparison, and analysis of hypotheses in systematic review*.

R Development Core Team. (2013). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing. http://www.R-project.org

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H. (2018). Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology*, *69*(1), 789–815. https://doi.org/10.1146/annurev-arplant-042817-040256

Rook, A. J., Dumont, B., Isselstein, J., Osoro, K., WallisDeVries, M. F., Parente, G., & Mills, J. (2004). Matching type of livestock to desired biodiversity outcomes in pastures – a review. *Biological Conservation*, *119*(2), 137–150. https://doi.org/10.1016/j.biocon.2003.11.010

Rook, A. J., & Tallowin, J. R. B. (2003). Grazing and pasture management for biodiversity benefit. *Anim. Res.*, *52*(2), 181–189. https://doi.org/10.1051/animres:2003014

Roscher, C., Schumacher, J., Lipowsky, A., Gubsch, M., Weigelt, A., Pompe, S., Kolle, O., Buchmann, N., Schmid, B., & Schulze, E.-D. (2013). A functional trait-based approach to understand community assembly and diversity-productivity relationships over 7 years in experimental grasslands. *Perspectives in Plant Ecology, Evolution and Systematics*, *15*(3), 139–149. Scopus. https://doi.org/10.1016/j.ppees.2013.02.004

Rosenthal, R. (1979). The file drawer problem and tolerance for null results. *Psychological Bulletin*, *86*(3), 638–641. https://doi.org/10.1037/0033-2909.86.3.638

Roy, J., Mooney, H. A., & Saugier, B. (2001). *Terrestrial Global Productivity* (1st edition). Academic Press.

Rustad, L., Campbell, J., Marion, G., Norby, R., Mitchell, M., Hartley, A., Cornelissen, J., Gurevitch, J., & GCTE-NEWS. (2001). A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia*, *126*(4), 543–562. https://doi.org/10.1007/s004420000544

Sala, O. E., Stuart Chapin, F., III, Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M., &

Wall, D. H. (2000). Global Biodiversity Scenarios for the Year 2100. *Science*, *287*(5459), 1770. https://doi.org/10.1126/science.287.5459.1770

Saladini, F., Betti, G., Ferragina, E., Bouraoui, F., Cupertino, S., Canitano, G., Gigliotti, M., Autino, A., Pulselli, F. M., Riccaboni, A., Bidoglio, G., & Bastianoni, S. (2018). Linking the water-energy-food nexus and sustainable development indicators for the Mediterranean region. *Ecological Indicators*, *91*, 689–697. https://doi.org/10.1016/j.ecolind.2018.04.035

Seibold, S., Gossner, M. M., Simons, N. K., Blüthgen, N., Müller, J., Ambarlı, D., Ammer, C., Bauhus, J., Fischer, M., Habel, J. C., Linsenmair, K. E., Nauss, T., Penone, C., Prati, D., Schall, P., Schulze, E.-D., Vogt, J., Wöllauer, S., & Weisser, W. W. (2019). Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature*, *574*(7780), 671–674. https://doi.org/10.1038/s41586-019-1684-3

Simopoulos, A. P., Bourne, P. G., & Faergeman, O. (2013). Bellagio Report on Healthy Agriculture, Healthy Nutrition, Healthy People. *Lifestyle Genomics*, *6*(1), 34–42. https://doi.org/10.1159/000346833

Šímová, I., & Storch, D. (2017). The enigma of terrestrial primary productivity: Measurements, models, scales and the diversity–productivity relationship. *Ecography*, *40*(2), 239–252. https://doi.org/10.1111/ecog.02482

Spangenberg, J. H., Görg, C., Truong, D. T., Tekken, V., Bustamante, J. V., & Settele, J. (2014). Provision of ecosystem services is determined by human agency, not ecosystem functions. Four case studies. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *10*(1), 40–53. https://doi.org/10.1080/21513732.2014.884166

Steffen, W. L., Carpenter, S., Tyson P., Jäger, J., Matson, P.A., Moore III, B., Oldfield, F., Richardson, K., Schellnhuber, H.J., Turner II, B.L., & Wasson, R.J. (2005). *Global change and the Earth system: A planet under pressure*. Springer.

Tenopir, C., Allard, S., Douglass, K., Aydinoglu, A. U., Wu, L., Read, E., Manoff, M., & Frame, M. (2011). Data Sharing by Scientists: Practices and Perceptions. *PLoS ONE*, *6*(6). https://doi.org/10.1371/journal.pone.0021101

Thompson, C. G., Kim, R. S., Aloe, A. M., & Becker, B. J. (2017). Extracting the Variance Inflation Factor and Other Multicollinearity Diagnostics from Typical Regression Results. *Basic and Applied Social Psychology*, *39*(2), 81–90. https://doi.org/10.1080/01973533.2016.1277529

Turner, M. G. (2010). Disturbance and landscape dynamics in a changing world. *Ecology*, *91*(10), 2833–2849. https://doi.org/10.1890/10-0097.1

URPP GCB. (2012). *Proposal document. Global change and biodiversity: Predicting the state of the environment: Integrating mechanisms of interactions, feedbacks and scale.* University Research Priority Programme Global Change and Biodiversity, University of Zurich.

Van Ruijven, J., & Berendse, F. (2003). Positive effects of plant species diversity on productivity in the absence of legumes. *Ecology Letters*, *6*(3), 170–175. https://doi.org/10.1046/j.1461-0248.2003.00427.x

Viechtbauer, W. (2010a). Conducting meta-analyses in R with the metafor package. *J Stat Software*, *36*. https://doi.org/10.18637/jss.v036.i03

Viechtbauer, W. (2010b). *Rma.mv function, Meta-Analysis via Multivariate/Multilevel Linear (Mixed-Effects) Models, metafor package documentation, R software*. rdocumentation.org. https://www.rdocumentation.org/packages/metafor/versions/1.9-9/topics/rma.mv

Waide, R. B., Willig, M. R., Steiner, C. F., Mittelbach, G., Gough, L., Dodson, S. I., Juday, G. P., & Parmenter, R. (1999). The relationship between productivity and species richness. *Annual Review of Ecology and Systematics*, *30*, 257–300.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J.-M., Hoegh-Guldberg, O., & Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, *416*(6879), 389–395. https://doi.org/10.1038/416389a

Wenhold, F. A. M., Faber, M., van Averbeke, W., Oelofse, A., van Jaarsveld, P., van Rensburg, J., van Heerden, I., & Slabbert, R. (2007). *Linking smallholder agriculture and water to household food security and nutrition*. *33*(3). http://dx.doi.org/10.4314/wsa.v33i3.180590

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag.

Wu, J. (2004). Effects of changing scale on landscape pattern analysis: Scaling relations. *Landscape Ecology*, *19*(2), 125–138.

Zavaleta, E. S., Pasari, J. R., Hulvey, K. B., & Tilman, G. D. (2010). Sustaining multiple ecosystem functions in grassland communities requires higher biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(4), 1443–1446. PMC. https://doi.org/10.1073/pnas.0906829107

Zuppinger-Dingley, D., Krug, C. B., Petchey, O., Schmid, B., Backhaus, N., & Schaepman, M. E. (2017). Editorial overview: Environmental change issues: Integrated global change and biodiversity research for a sustainable future. *Current Opinion in Environmental Sustainability*, *29*, vii–xi. https://doi.org/10.1016/j.cosust.2018.05.019

4.7 Supplementary material

Appendix S1 - Figures

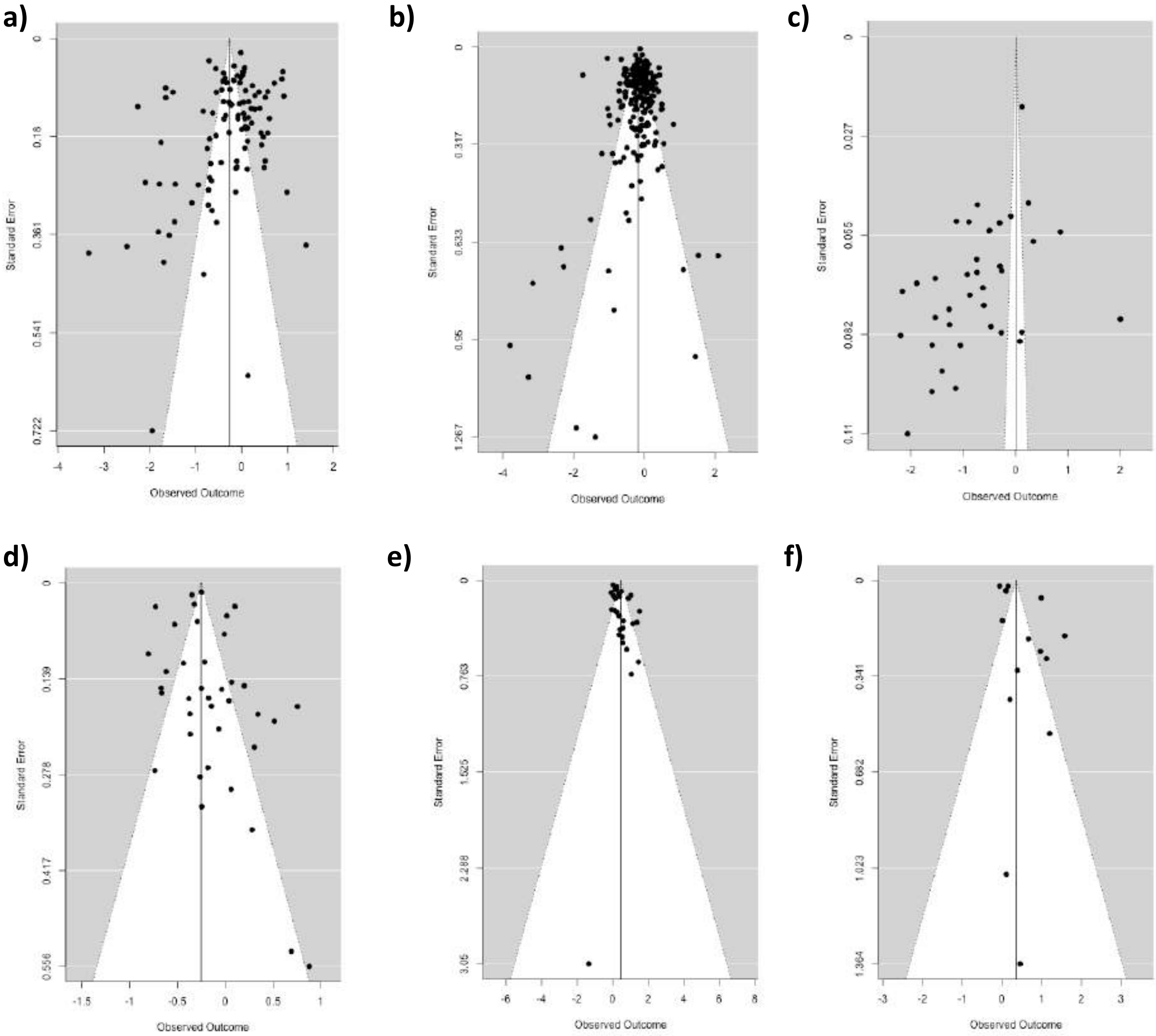

Fig. 4.S1.1: Funnel plot showing symmetry of effects around the average for a) land use conversion effects on biodiversity, b) land use intensification effects on biodiversity, c) land use conversion effects on productivity, d) land use intensification effects on productivity, e) biodiversity effects on productivity, f) land use change effects on nutritional status

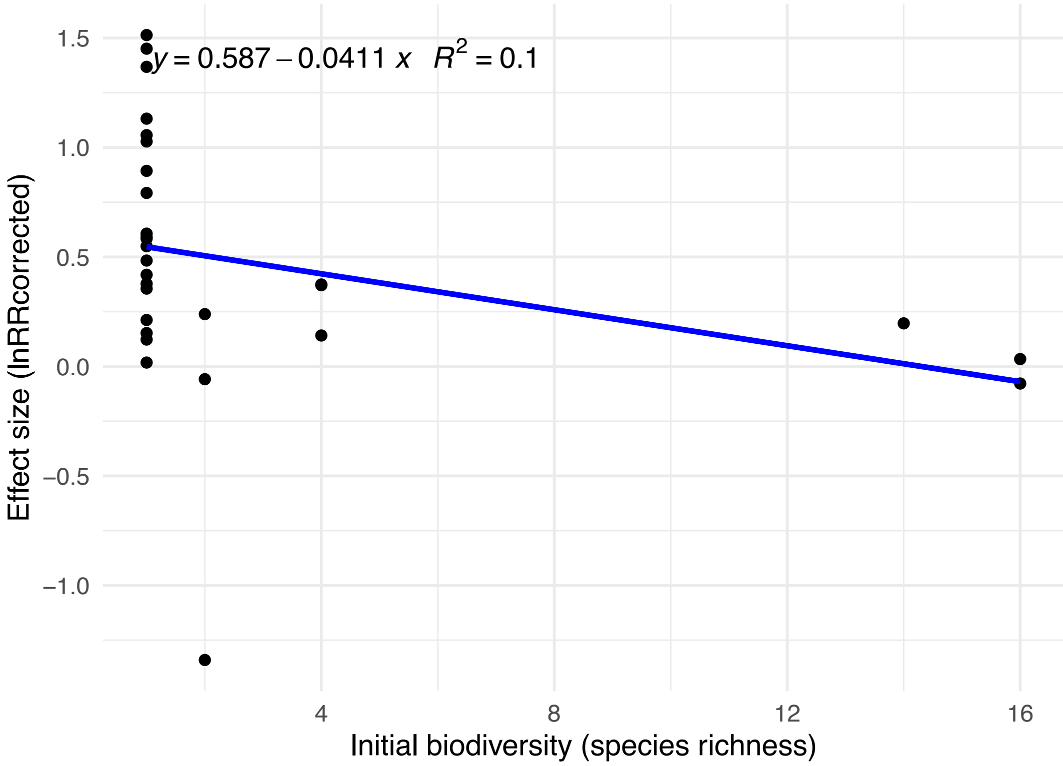

Fig. 4.S1.2: Effects of biodiversity on productivity, by the initial biodiversity level in plots.

Appendix S2 - Tables

Table 4.S2.1: Fail safe n and Egger tests for meta-analyses for a) land use (LU) effects on biodiversity (BD), b) land use effects on productivity, c) biodiversity effects on productivity (NPP), ***p<0.005

a)	LUConversion_BD	LUIntensification_BD
Fail-safe n	9513***	33355***
Egger test	y= 0.121 -4.093x	Y= 0.07749-1.24738x

b)	LUConversion_NPP	LUIntensification_NPP
Fail-safe n	47592***	4292***
Egger test	y= 9.37E-3 -1.47e+02x	y= -0.03479 +3.44944x

c)	BD_NPP
Fail-safe n	1525
Egger test	y= 0.09491 – 0.19198x

d)	LU_NUT
Fail-safe n	872
Egger test	y= 0.20282 – 0.09639x

Table 4.S2.2: Review of papers on land use change effects on nutritional status, that were not considered for a quantitative analysis but contained important concepts and conclusions to frame the interaction.

Citation	Effect variable	Response variable, Socio-economic index	Type of analyses	Conclusion	Availability of associated data	Country
(Cholo, Fleskens, Sietz, & Peerlings, 2019)	Land fragmentation, Climate, Agricultural practices	Food security (gross household food production; caloric intake per household in the last 24 hours, coping strategies, household food insecurity access scale, household dietary diversity scale)	Survey analysis (qualitative and quantitative). Case study.	High insecurity rates, exacerbated by climate change and seasonality, outweigh sustainable practices benefits. Land fragmentation can have a positive or negative effect on food security but shows potential for progress.	Summary values and correlations correlation coefficients, all reported in the paper	Ethiopia
(Mattsson, Ostwald, & Nissanka, 2018)	Home garden and multifunctional land use systems (e.g., agroforestry)	Food security	Review	Most articles studying this relation report indirect effects, not direct ones (via ecosystem services, economic aspects, climate, soil, structural and floristic diversity). Most studies are descriptive. Few comparisons between production systems, despite high promotion through national policies.	No data associated (description of the literature)	Sri Lanka
(Nogeire-McRae et al., 2018)	Urban agriculture (different types and sizes of urban gardens)	Economy (job creation, new capital, property values, taxes). Public health (Fresh produce consumption, dietary diversity, reduced agrochemicals, contamination in produce, food security, food security).	Review	Research gaps on every response variable measured. Lack of reliable data on micronutrients and intake from vegetables grown under different agricultural practices. Conservation impacts poorly understood.	Large scale, descriptive quantitative data (summary from reviews), in charts	United States

		Conservation impact (climate change adaptation, biodiversity, water, land)				
(Saladini et al., 2018)	Sustainable practices in agriculture	Food security and sustainable management of water (multidimensional poverty index, population overweight, land use, emissions, cereal yield, agriculture value added, fertilizer consumption, crop water productivity, annual freshwater withdrawal for agriculture, population with safe water service, population with sanitation service, amount of agricultural residues used as energy.	Conceptual, Methodological, Case study	Lists useful specific indicators to monitor and describes them. Lists sources of national databases for finding data to calculate them. Quantifies a baseline using available datasets. Compiles local level information for some of the indicators and graphic outputs.	Large scale, data of the World Bank, WHO, FAO, UNFCCC, for Mediterranean countries. Specific data used for case study, not immediately available.	Mediterranean countries
(Berners-Lee, Kennelly, Watson, & Hewitt, 2018)	Land use change (conversion/intensification), Increase in productivity	Global and regional food security (energy requirements, amount and type of nutrients)	Modelling towards 2050, based on current production and consumption patterns.	There is enough production in yield and nutritional content of crops to feed the population of the world in 2050, but adaptations in changes of diet, global flows (distribution) will have to occur.	Large scale, data from national and international departments.	Global

(Bouttes, San Cristobal, & Martin, 2018)	Climate changes, economic changes, farm practices	Food security understood as Vulnerability of farms (related to variability in productivity and economic efficiency) - focused on organic farms	Case study	Individual farms exhibit specific trajectories and tradeoffs, and the main causes for them differ between farms with a combination of different factors. Greater production not always led to greater earnings: fine tuning inputs and aiming for self-sufficiency were key in obtaining best results. In this case of organic farms, it was not possible to obtain economic efficiency and increase productivity at the same time.	Correlation coefficients presented in results. Graphical depiction of trajectories over time.	France
(Ramankutty et al., 2018)	Land use change (conversion/intensification)	Environmental health, food security	Historical Review, Perspective	We are able to feed theoretically the global population, at the expense of polluting the environment and a decrease in biodiversity. Although there has been an improvement in human nutrition, there are still areas where malnutrition and obesity are endemic. There is a need to link modern technologies for plant breeding and farm practices. Funding should be redirected to sustainable agriculture; which in turn should increase productivity and ensure food security.	No data associated (other than reported trends in the text)	Global
(Chyne et al., 2017)	Socio-economic variables (income, literacy, family size)	Nutritional status (anthropometric measures, underweight, stunting, wasting, nutrient levels), Health (anemia, hypertension), Food security (food insecurity experience scale FAO, dietary diversity, average consumption),	Case study	Undernutrition was high even despite access to rich food biodiversity, both wild and cultivated. Education on nutrition is required to make use of available resources. Gender issues may prevent education to actually have an impact on malnutrition prevention. Local genetic characteristics that have not be studied could be confounding effects when analyzing anthropometric measures against international standards. Intensive agriculture poses threats to wild biodiversity, which would actually increase the nutritional status if used.	Correlation coefficients, summary graphics to compare populations	India

(Wood, 2018)	Nutritional functional diversity farming	Nutritional status (potential)	Methodological and modelling under different land use scenarios, based on data from a case study (descriptive)	Identifies crops with complementary nutritional values. Identifies the practices from the "African Green Revolution" as the scenario with the greatest potential to fit the nutritional demands of the population. Develops a new index to measure nutritional content based on functional traits from the plants. Mentions limitations of measuring impacts on nutritional status using nutritional content of food as a proxy (e.g., assimilation is not equal to ingest)	Summary descriptive data in paper tables and graphics. No further data associated.	Senegal
(Jones, 2017)	Agricultural biodiversity	Anthropometric measures, diet quality	Semi-quantitative Review	Results suggest a small association of agricultural biodiversity with diverse diets and improvements in some anthropometric indexes (but not in the majority analyzed). Suggests conceptual network diagrams for the effects, including socio-economical aspects. Identifies research gaps and lists priorities (one of them is research design, another one is assessment of health impacts)	Systematic review of 23 studies that reported correlations between agricultural practices of increased biodiversity and dietary diversity or anthropometric measures. Effect sizes not possible to calculate. Correlation coefficients reported as associations (and the strength of it).	Low-middle income countries
(Hauck & Rubenstein, 2017)	Globalization, climate change, changes in land productivity	Land use practices, Socio economical indexes (e.g., Gini), migration patterns, nutritional status	Case study (longitudinal study)	Highlights importance of rainfall, productivity variations and climate in farmers decision making (e.g., migration patterns, choice of practices). Highlights the differential impact on different parts of the population due to baseline inequalities in wealth and social structures. Defines the term "survival economy".	Temporal scales in climate and agroecological indexes depicted graphically. Mean and errors of socio-economical indexes. Correlation coefficients.	Kenya

(Ickowitz, Rowland, Powell, Salim, & Sunderland, 2016)	Swidden cultivation practices and wild produce collection	Nutritional status (dietary quality, consumption of food types rich in micronutrients)	Case study	Highlights the caveats of working with national data and trying to draw conclusions at a local level. Conclusions are sometimes opposite between the two scales, and even between close regions with different cultures. Overall results suggest that forests and landscape has an influence on nutritional status of local populations and should be taken into account in policies to improve intake of micronutrients. Traditional practices of agroforestry had a positive correlation with nutritional status.	Raw data from central government surveys. Means and errors on key varia-bles presented. Correlation coeffi-cients.	Indone-sia
(Kumar, Harris, & Rawat, 2015)	Agricultural biodiversity	Dietary diversity, an-thropometric measures	Case study	Production diversity had an important impact on young children nutritional status. Current policies to increase stable crops through intensification do not promote diversification of household produc-tion (same as in the previous example in Indonesia, with rice).	Correlation coeffi-cients presented in results. Summary values and raw data not immedi-ately available.	Zambia
(Maluf, Burlandy, Santarelli, Schottz, & Speranza, 2015)	Nutrition sen-sitive agricul-ture	Nutritional status	Review	Concept that links agricultural practices to popula-tion's nutritional needs for a healthy life, usually coupled with environmental protection goals. It lists benefits, potentials and current programs spe-cific to the country that would fit with the require-ments.	No data associated (description of the literature)	Brazil
(Allen, Prosperi, Cogill, & Flichman, 2014)	Agricultural biodiversity	Nutritional status, environmental degra-dation	Conceptual, per-spective	Agricultural biodiversity is key to ensure a nutri-tious food supply. Modeling techniques are im-portant tools to work interdisciplinary linking bio-logical and human systems and decision making processes. Food consumption behavior is a driving force for agricultural practices.	Agricultural biodi-versity is key for providing a healthy food supply	Global

(Rahman & Islam, 2014)	Nutrition sensitive agriculture (Land use patterns)	Food security(daily food consumption, dietary diversity), Nutritional status (micronutrient intake, calorie intake), socioeconomic indexes (household income)	Review, monitoring of local programs	Nutrition sensitive programs have been positive in qualitative terms for the development of rural poor populations and nutritional status has overall increased. Malnutrition is focused on micronutrients, particularly in risk groups (young children and pregnant mothers). These programs should be coupled with educational ones on nutrition. NGO's efforts and consideration for women gender issues is essential to the success of land interventions.	Use of nation-wide data from centralized government. Presents means with no errors.	Bangladesh
(Godfray & Garnett, 2014)	Land use change (conversion/intensification)	Food security, environmental degradation, governance	Conceptual, perspective	Conceptualizes global food policy, as a function of production and demand policies, defining price, in a framework of governance, international goals to develop and end hunger, trade and environmental degradation. Suggests tools from all forms of agriculture should be considered. Discusses policy implications of certain ambiguous terminology, such as "intensification".	No data associated (description of the literature)	Global
(Simopoulos, Bourne, & Faergeman, 2013)	Agriculture	Health	Position paper, perspective	Participants of a meeting concluded on a list of recommendations to improve our knowledge and interventions on agriculture and health programs. The key suggestions are: improving translation from science to policies, awareness of detrimental production/consumption of sugars and importance of specific micronutrients and macromolecules to prevent diseases, importance of developing national food composition tables and education in nutrition, understanding that not every practice or need is the same across countries, role of genetics, role of economics and political contexts that allow for change.	No data associated (description of the literature)	Global

(Hammond & Dubé, 2012)	Agriculture, infrastructure, global change	Food and nutrition security	Conceptual	Developing solutions to tackle malnutrition and obesity requires a system approach, given the multiple factors affecting food availability, food intake, personal decisions and disease.	No data associated (description of the literature)	Global
(Haberl, 2015)	Land use changes (productivity), Diets, Climate change	Food security (Bioenergy production)	Modelling towards 2050, based on current land use, primary production and human appropriation of productivity and socioeconomic indexes	Bioenergy is the energy derives from raw biological materials, that we require for our society to develop. The study models the amount of bioenergy needed in 2050, and concludes diet driven food and livestock requirements are a strong influence, as well as climate change but the effects of the latter are more uncertain. Strong emphasis on the importance of quantifying biomass needed to supply the food and energy demand.	Use of a database found online (in the university of Vienna), with nationwide level data on land use and socioeconomic indexes for several countries. Present summary data for all variables used in the model, correlation coefficients and graphical depictions of the outcome of different models of land use.	Global
(Dame & Nüsser, 2011)	Monetary income, Globalization	Land use practice, Dietary shifts, Food security, Nutritional status (micronutrients)	Case study	Stresses the seasonality of dietary diversity, which in turn determined periods of food insecurity. Monetary income is important in determining the household strategies. Safety net programes help tackle insecurity. Suggests not to narrow policies to productivity or income, but to analyze case by case the interplay between different stakeholders.	Present frequency of consumption of each type of food, per season	India

(Pasricha & Biggs, 2010)	Multiple socio-economical causes	Nutritional status (anthropometric measures, underweight, stunting, wasting, nutrient levels)	Conceptual and Review	Undernutrition has immediate and distal causes, that are exacerbated when production is reduced, there is a crisis and food prices go up. Children are among the most vulnerable to undernutrition, and the stage of development in which they are deprived from full nutritional diet, can be identified by some and not all for the anthropometric indexes in the same way. Furthermore, each stage (wasting, stunting and undernutrition) reflects different processes, that can be caused by a combination of factors. Poverty alone, measured as income, does not explain or correlate directly with malnutrition levels. Nutritional supplements are effective but costly.	Summary data from nationwide organizations across South Asian countries	South and South East Asia
(Ostry & Morrison, 2010)	Agriculture	Health	Case study	Food production and land use patterns have historically gone in the opposite direction than that recommended by nutritionists. Trade plays a role in the type of consumption patterns observed.	Used nationwide data from census. Present summary figures. No data on nutritional status.	Canada
(Alderman, 2009)	Climate change	Nutritional status	Review	Climate change produces periodic or punctual losses in food production and stock, that in turn affect the nutritional status of the population, leaving marks, especially in children. Safety nets provided by organizations can be effective in preventing major effects on children development. However more research is needed, for example on cost-efficiency of these methods.	No data associated (description of the literature)	Low income countries
(Graham et al., 2007)	Sustainable practices in agriculture	Nutritional status, productivity	Book, review, conceptual, case studies	Comprehensive view of the whole system	Nationwide data from census	Global
Giampietro 1997	Agricultural biodiversity	Environmental degradation, Economic efficiency of farms, Productivity	Conceptual and Review	Biodiversity in farms is costly and above a certain threshold impractical	Nationwide data from central organizations	Global

Table 4.S2.3: Review of papers on diet shifts effects on land use changes

Citation	Effect variable	Response variable	Type of analysis	Conclusions	Availability of associated data	Country
(Aleksandrowicz et al., 2019)	Shift to healthier diets (increase meat and vegetable intake) and shifts to affluent (wealthy) diets (more energy content)	Carbon emissions, land use and water footprint	Modelling	Shifts to healthier diets will increase the impact on the environment, particularly on carbon emissions, land use and water footprint. However, the impact would be smaller that if the populations switches to affluent diets. There are differences between the footprint of rural and urban areas (usually urban is slightly higher)	Nationwide data	India
(Baudry et al., 2019)	Proportion of organic food consumption	Nutritional status, dietary monetary cost, environmental impact	Case study, Modelling	Higher organic food consumption was correlation with consumption of a healthy diet and lower BMI. They also had less environmental impact (except for certain pesticides).	Case study data, summary data and correlations presented in paper (data not immediately available)	France
(Song et al., 2019)	Shift to healthier diets, in urban environments	Environmental impact	Case study, Modelling	Age and gender specific results. Sedentarism in urban settings has an influence in nutritional status and environmental impact of diet.	Nationwide data, some models based on data from Europe, in the absence of Chinese data	China
(Mertens et al., 2019)	Higher dietary quality	Environmental impact	Methodological	Comparing two ways of estimating environmental impact of diets (individual based): 24 hs recalls and FFQ (food frequency questionnaire). Estimations were dependent on the method. There is an association between dietary quality, not only amount or diversity, and environmental impact: higher dietary quality leads to less environmental impact: nutrient-based approaches would be important to both improve nutritional status and reduce environmental impact.	Data from a case study to test the model. Data not immediately available (summary data in paper)	Netherlands

(Zech & Schneider, 2019)	Shift to healthier diets (low-meat)	Biofuel production and carbon emissions	Modelling	Reducing carbon emissions would free space for crops that can be transformed in biofuel, reducing the use of fossil fuels and therefore carbon emissions. Emphasis in using consumer preferences in the models, and not only theoretical healthy diets.	Nationwide data and international databases data	EU
(Rizvi, Pagnutti, Fraser, Bauch, & Anand, 2018)	Shift to a healthier diet (increase in vegetables and food)	Impact on land use (amount)	Modelling	There is not enough land for everyone in the world to be fed with a healthy diet as recommended by policies in the United States. Some countries could meet the goal by reducing the amount of land used for meat production (e.g., in South America, Asia and Africa) and other would have to expand the current agricultural land for crops (e.g., Europe)	Nationwide data and international databases data (historical). Code and data available in supplementary material.	Global
(Seconda et al., 2018)	Higher dietary quality	Carbon emissions	Case study, Modelling	Higher dietary quality was again correlated with lower environmental impact.	Same case study (possibly different dataset within the network), as Baudry et al. 2019.	France
(Gephart et al., 2016)	Maximizing nutrient content and lower environmental impact	Environmental impact	Modelling	Their idea is to optimize nutrient content in diets, to reduce the maximum possible the environmental impact. Plant-seafood diets could help reduce environmental impact while keeping nutritious diets. Reducing impacts in one dimension (e.g., water footprint) could increase impact in others (e.g., carbon emissions), so multiple of them should be taken into account.	Nationwide data	United States
(Macdiarmid, 2014)	Eating seasonal food	Health, environmental impact	Review	Definitions for seasonality/grown outdoors/local vary, as well as the scales that they imply and therefore the impacts of different "seasonal" diets vary too. Carbon emissions depend more on the system of production than on the transportation.	no data associated	Global

(Odegard & van der Voet, 2014)	Increase in population, keeping current diet	Environmental impact	Modelling	Whenever modeling, land use and fertilizer, as well as water use should be all taken into account. High waste and high protein/meat consumption are major contributors to the global demand.	Data taken from peer reviewed publications and nationwide data (data in supplementary material)	Global
(Risku-Norja, Hietala, & Virtanen, 2008)	Organic vs traditional practices and diet shift	Environmental impact (nutrient valances, greenhouse gas emissions, acid emissions, diversity of crops)	Case study, Modelling	Found conflicting interests between economy and environment are the ones responsible for counter-intuitive things, like exporting produce when local demand is not satisfied, or importing even when it is. Vegetarian options are better for environmental impact, but not necessarily represent more diverse diets and it was not optimal on the conservation of wild species. Eating localized foods that are environmentally not friendly, does not remove the damaging effects from environment. The term "local" needs to be revised and defined.	Data in paper (summary, no errors)	Finland
(Gerbens-Leenes & Nonhebel, 2005)	Diet shifts	Land requirements	Modelling	Current consumption patterns of the wealthy population require 6 times more land space than a hypothetical basic diet. Demand for products like cheese, beverages, fruits and meat are major drivers of land use changes.	Nationwide data	Netherlands

Appendix S3 – Protocol

Literature search

The literature search was performed in Web of Science, with the terms shown in Table A3.1. Results in number of studies found, read and analyzed are shown in Table A3.2.

Table 3.S3.1 Terms and keywords

Interaction	Terms
LU->BD	(“land use” and (“species richness” or biodiversity or “biological diversity”) (years 2000-2017)
LU->NPP	(“land use ” and “net primary productivity”) (years 2000-2017)
BD->NPP	(“species richness” or biodiversity or "biological diversity") and (biomass OR productivity) (years 2000-2017)
LU->NUT /NUT->LU	(“land use” or “land use change” or “land use intervention” or “agro-ecology” or “agroecology”) and (“anthropometric” or “nutritional status” or “stunted” or “bmi”) – Refined by research domain: social sciences (years 2000-2019)

Table 4.S3.2 Efforts Literature Search

Interaction	Found	Read Title	Read Abstract and Results	Meta-analysis	Semi-quantitative and Qualitative analyses	Authors contacted for data
LU->BD	8644	753	235	62	NA	34
LU->NPP	5648	215	50	11	NA	3
BD->NPP	5215	100	51	7	NA	0
LU->NUT /NUT->LU	796	796	95	7	35	4

Rejection/inclusion criteria

1) Quantitative analyses (meta-analysis)

We rejected papers:

- that did not include the variables of interest as defined in the glossary
- that reported unique and non-comparable indexes (e.g., combinations of typical biodiversity measurements like species richness and Shannon index, in one index that is not used by any other study)
- that were qualitative or semi-quantitative (e.g., vote counting)
- that were observational studies without clear direction of causality between the variables of interest reported
- that reported correlation coefficients as effect sizes, and where there was no way to calculate means and error from the reported or shared data (reason: although the slope of a correlation can be considered for meta-analysis, we selected log response ratio – and originally standard deviation coefficients – and effect sizes from correlations cannot be mixed in the same analysis) (Koricheva, Gurevitch, & Mengersen, 2013)
- that did not report errors (standard errors or deviations) for means among replicates
- that were modelling studies without a case study dataset (except for reports on net primary productivity

2) Semi-quantitative and qualitative review of land use change -> nutritional status interactions

We rejected papers:

- that did not report on a land use change activity or status of a global change driver (e.g., carbon emissions, water footprint)
- that did not report a conclusion related with the nutritional status of a community or one of the proxies and related variables of the system (e.g., health status and food security)

Definition of Variables/Glossary

- **Altitude:** measured in meters above sea level (m.a.s.l). When not reported but coordinates reported exactly, then calculated using a free online service at elevationmap.net and Google Earth Software.
- **Average effect size:** it is the average effect, calculated from all original studies that reported an effect between two variables. In the last version of the analysis, log response ratio (ln RR) is presented for the average effect sizes.
- **Biodiversity measurements:** quantitative indexes used by researchers to define the biodiversity level of an area (most commonly, the number of species present)
- **Coordinates:** geographical coordinates where the data was collected Lat, Long). When several points close in space are studied and pooled, then the coordinates belong to the center between the points. When points that are very far apart (like different regions of a country or countries), the center is computed but a note in comments should indicate it. Coordinates are computed in decimals (long-lat in different columns), transformed using a free online service at andrew.hedges.name/experiments/convert_lat_long/ and Google Earth Software.
- **Diet shifts:** changes in composition and amount of products in the diet of a community or in an individual, over time (i.e. affluent diet: diet typically sustained by the wealthier people in the country)
- **Earth/World system:** the global system of linked ecological and social subsystems, as defined, for example, by (Abel et al., 2006).
- **Ecosystem:** mayor biome of the area of study (>51%): when largely mixed as defined by authors, noted as the combination of the major types (e.g., Mixed Forest and Grassland). When absent in the original study, located with coordinates of study sites using Google Earth Software. Defined according to Figure 11.23, chapter 11 from the book Physical Geography (Gabler et al. 2008). Major ecosystems considered: Tropical Rainforest (includes Monsoon Forest), Mediterranean Middle-Latitude Forest, Broad-Leaf and Mixed Middle, Latitude Forest, Coniferous Forest, Tropical Grassland, Middle-Latitude and

Border Tropical Grassland, Tundra and Alpine Meadow, Desert Vegetation. Pooled into three categories: forest, grassland and shrubland for main analysis.

- **Effect sub-variable:** specific variable assumed by authors to be the responsible for the outcomes observed in the response variable (e.g., for land use change effect variable, animal pasture, agriculture, agroforestry and urbanization are subvariables).
- **Effect variable:** broad variables assumed by authors to be the responsible of outcomes observed in the response variable (e.g. for land use change activities).
- **Errors:** SD: standard deviation; SE: standard error. Unless specified otherwise, errors in the graphs are standard deviations.
- **Extent:** area of land in which the plots were dispersed, in experimental studies.
- **Geographical scale:** this is the extent of area in which the conclusions are valid or intended for the author: global (data comes from several countries and ecosystems or was modelled with global satellite/statistical data); regional (data comes from several distant points in the same country or region and refer to regional phenomena); local (close points of study in the same country or in close boarders of countries, laboratory experiments, local data used for modelling, plots in the same or very close area, small scale phenomena treated)
- **Global-change driver:** effect variables of the Earth/World system that produce significant changes overtime in the landscape, natural resources and human well-being.
- **Human production activity**: any type of land use modification that contributes to human society through the products and services it leads to (e.g., forestry, for provision of food, timber and financial income).
- **Intensity (for land use changes):** strength of an activity, measured in the units of the sub-variable of interest (e.g., for animal pasture: density of cattle heads per area defines low, intermediate or high). Follows descriptions by original authors whenever present in original studies. Naturally a continuous variables, made discrete for the purpose of defining means across ranges of intensity.

- **Land use change:** any type of land use modification (baseline landscape not defined)
- **Land-use type:** changes in a native landscape related to beginning a new human production activity.
- **Land-use intensity**: changes in a modified landscape related to the increase in intensity of a human production activity.
- **Land-use alteration:** changes in a modified landscaped related to the change in type of activity (usually from abandoned to production)
- **Mean response variable:** Average of the response variable quantified in original studies.
- **Number of observations:** for each study, is defined as the number of replicated in treatment and control (used to weight the effect sizes). In graphs, noted next to effect variables, it is the number of independent observations from original studies that measured for one interaction.
- **Nutritional status:** anthropometric measures and key micronutrient level in a community
- **Primary productivity/Biomass:** production of biomass in time, per area
- **Qualitative analysis:** it is the description of the commonalities and differences in the conclusions that a set of papers arrived to, but that could not be used for a meta-analysis.
- **Quantitative analysis:** we refer strictly as quantitative analysis, to a meta-analysis done with a set of studies obtained through systematic search of the literature.
- **Response variable:** Broad variable in which the effect was measured (in notation, always to the right size of an equation – e.g., LUI->BD : Land use intensification effect on biodiversity)
- **Semi-quantitative analysis:** it is a quantification of the properties of studies found in the literature to have important conclusions for the interaction of interest, but that were not included in the meta-analysis.
- **Species Richness:** number of species, per area
- **Taxa:** Taxonomic group to which the species belong, generally consistent with the classification of “phylum”.

- **Temporal scale:** total duration of the sampling, experiment or amount of time to which the data used corresponds to (when extracted from library). When the sampling was done in 1-2-3 months, it is coded as Season. When it was done in several seasons so that annual or inter-annual variability can be accounted for, its coded Year. When it was done with an experiment in less than month, it is coded “Point”.
- **Type of study:** Whether the data corresponds to an observational (field collection, including traps) or experimental study (semi-field artificial setup or laboratory setup). For land use-biodiversity interaction and land use-nutritional status, modelling and prediction studies were largely omitted given the different nature of controls, number of observations and measurements. For primary productivity, remote sensing and satellite studies are considered observational, when available summary data could be extracted.

References Supplementary Material

Abel, T., Berglund, B., Chase-Dunn, C., Crosby, A., Crumley, C., Dearing, J., … Turchin, P. (2006). *The world system and the earth system: Global socioenvironmental change and sustainability* (Left Coast Press, Inc.). U.S.A.: Alf Hornborg and Carole Crumley (Eds).

Alderman, H. (2009). Safety Nets Can Help Address the Risks to Nutrition from Increasing Climate Variability. *The Journal of Nutrition*, *140*(1), 148S-152S. https://doi.org/10.3945/jn.109.110825

Aleksandrowicz, L., Green, R., Joy, E. J. M., Harris, F., Hillier, J., Vetter, S. H., … Haines, A. (2019). Environmental impacts of dietary shifts in India: A modelling study using nationally-representative data. *Environment International*, *126*, 207–215. https://doi.org/10.1016/j.envint.2019.02.004

Allen, T., Prosperi, P., Cogill, B., & Flichman, G. (2014). Agricultural biodiversity, social–ecological systems and sustainable diets. *Proceedings of the Nutrition Society*, *73*(4), 498–508. https://doi.org/10.1017/S002966511400069X

Baudry, J., Pointereau, P., Seconda, L., Vidal, R., Taupier-Letage, B., Langevin, B., … Kesse-Guyot, E. (2019). Improvement of diet sustainability with increased level of organic food in the diet: Findings from the BioNutriNet cohort. *The American Journal of Clinical Nutrition*, *109*(4), 1173–1188. https://doi.org/10.1093/ajcn/nqy361

Berners-Lee, M., Kennelly, C., Watson, R., & Hewitt, C. N. (2018). *Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. 6*(1). https://doi.org/10.1525/elementa.310

Bouttes, M., San Cristobal, M., & Martin, A. (2018). *Vulnerability to climatic and economic variability is mainly driven byfarmers'practices on French organic dairy farms*. *94*(89–97).

Cholo, T. C., Fleskens, L., Sietz, D., & Peerlings, J. (2019). Land fragmentation, climate change adaptation, and food security in the Gamo Highlands of Ethiopia. *Agricultural Economics*, *50*(1), 39–49. https://doi.org/10.1111/agec.12464

Chyne, D. A. L., Meshram, I. I., Rajendran, A., Kodali, V., Getti, N., Roy, P., … Longvah, T. (2017). Nutritional status, food insecurity, and biodiversity among the Khasi in Meghalaya, North-East India. *Maternal & Child Nutrition*, *13*(S3), e12557. https://doi.org/10.1111/mcn.12557

Dame, J., & Nüsser, M. (2011). Food security in high mountain regions: Agricultural production and the impact of food subsidies in Ladakh, Northern India. *Food Security*, *3*(2), 179–194. https://doi.org/10.1007/s12571-011-0127-2

Gephart, J. A., Davis, K. F., Emery, K. A., Leach, A. M., Galloway, J. N., & Pace, M. L. (2016). The environmental cost of subsistence: Optimizing diets to minimize footprints. *Science of The Total Environment*, *553*, 120–127. https://doi.org/10.1016/j.scitotenv.2016.02.050

Gerbens-Leenes, W., & Nonhebel, S. (2005). Food and land use. The influence of consumption patterns on the use of agricultural resources. *Appetite*, *45*(1), 24–31. https://doi.org/10.1016/j.appet.2005.01.011

Godfray, H. C. J., & Garnett, T. (2014). *Food security and sustainable intensification*. *369*(1639). https://doi.org/10.1098/rstb.2012.0273

Graham, R. D., Welch, R. M., Saunders, D. A., Ortiz-Monasterio, I., Bouis, H. E., Bonierbale, M., … Twomlow, S. (2007). Nutritious Subsistence Food Systems. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 92, pp. 1–74). https://doi.org/10.1016/S0065-2113(04)92001-9

Haberl, H. (2015). Competition for land: A sociometabolic perspective. *ECOLOGICAL ECONOMICS*, *119*, 424–431. https://doi.org/10.1016/j.ecolecon.2014.10.002

Hammond, R. A., & Dubé, L. (2012). A systems science perspective and transdisciplinary models for food and nutrition security. *Proceedings of the National Academy of Sciences*, *109*(31), 12356. https://doi.org/10.1073/pnas.0913003109

Hauck, S., & Rubenstein, D. I. (2017). Pastoralist societies in flux: A conceptual framework analysis of herding and land use among the Mukugodo Maasai of Kenya. *Pastoralism*, *7*(1), 18. https://doi.org/10.1186/s13570-017-0090-4

Ickowitz, A., Rowland, D., Powell, B., Salim, M. A., & Sunderland, T. (2016). Forests, Trees, and Micronutrient-Rich Food Consumption in Indonesia. *PLOS ONE*, *11*(5), e0154139. https://doi.org/10.1371/journal.pone.0154139

Jones, A. D. (2017). Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. *Nutrition Reviews*, *75*(10), 769–782. https://doi.org/10.1093/nutrit/nux040

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). *Handbook of meta-analysis in ecology and evolution*. https://doi.org/10.1515/9781400846184

Kumar, N., Harris, J., & Rawat, R. (2015). If They Grow It, Will They Eat and Grow? Evidence from Zambia on Agricultural Diversity and Child Undernutrition. *The Journal of Development Studies*, *51*(8), 1060–1077. https://doi.org/10.1080/00220388.2015.1018901

Macdiarmid, J. I. (2014). Seasonality and dietary requirements: Will eating seasonal food contribute to health and environmental sustainability? *Proceedings of the Nutrition Society*, *73*(3), 368–375. https://doi.org/10.1017/S0029665113003753

Maluf, R. S., Burlandy, L., Santarelli, M., Schottz, V., & Speranza, J. S. (2015). Nutrition-sensitive agriculture and the promotion of food and nutrition sovereignty and security in Brazil. *CiÃ\textordfemeninencia & SaÃºde Coletiva*, *20*, 2303–2312.

Mattsson, E., Ostwald, M., & Nissanka, S. P. (2018). What is good about Sri Lankan homegardens with regards to food security? A synthesis of the current scientific knowledge of a multifunctional land-use system. *Agroforestry Systems*, *92*(6), 1469–1484. https://doi.org/10.1007/s10457-017-0093-6

Mertens, E., Kuijsten, A., Geleijnse, J. M., Boshuizen, H. C., Feskens, E. J. M., & van't Veer, P. (2019). FFQ versus repeated 24-h recalls for estimating diet-related environmental impact. *Nutrition Journal*, *18*(1), 2. https://doi.org/10.1186/s12937-018-0425-z

Nogeire-McRae, T., Ryan, E. P., Jablonski, B. B. R., Carolan, M., Arathi, H. S., Brown, C. S., … Schipanski, M. E. (2018). The Role of Urban Agriculture in a Secure, Healthy, and Sustainable Food System. *BioScience*, *68*(10), 748–759. https://doi.org/10.1093/biosci/biy071

Odegard, I. Y. R., & van der Voet, E. (2014). The future of food—Scenarios and the effect on natural resource use in agriculture in 2050. *Ecological Economics*, *97*, 51–59. https://doi.org/10.1016/j.ecolecon.2013.10.005

Ostry, A., & Morrison, K. (2010). A Health and Nutritional Evaluation of Changes in Agriculture in the Past Quarter Century in British Columbia: Implications for Food Security. *International Journal of Environmental Research and Public Health*, *7*(6). https://doi.org/10.3390/ijerph7062653

Pasricha, S.-R., & Biggs, B.-A. (2010). Undernutrition among children in South and South-East Asia. *Journal of Paediatrics and Child Health*, *46*(9), 497–503. https://doi.org/10.1111/j.1440-1754.2010.01839.x

Rahman, K. M. M., & Islam, M. A. (2014). Nutrition-sensitive agriculture in Bangladesh: A review. *Food Security*, *6*(5), 671–683. https://doi.org/10.1007/s12571-014-0380-2

Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H. (2018). Trends in Global Agricultural Land Use: Implications for

Environmental Health and Food Security. *Annual Review of Plant Biology*, *69*(1), 789–815. https://doi.org/10.1146/annurev-arplant-042817-040256

Risku-Norja, H., Hietala, R., & Virtanen, H. (2008). Localisation of primary food production in Finland: Production potential and environmental impacts of food consumption patterns. *Agricultural and Food Science*, *17*(2), 127–145. https://doi.org/10.2137/145960608785328233

Rizvi, S., Pagnutti, C., Fraser, E., Bauch, C. T., & Anand, M. (2018). Global land use implications of dietary trends. *PLOS ONE*, *13*(8), e0200781. https://doi.org/10.1371/journal.pone.0200781

Saladini, F., Betti, G., Ferragina, E., Bouraoui, F., Cupertino, S., Canitano, G., … Bastianoni, S. (2018). Linking the water-energy-food nexus and sustainable development indicators for the Mediterranean region. *Ecological Indicators*, *91*, 689–697. https://doi.org/10.1016/j.ecolind.2018.04.035

Seconda, L., Baudry, J., Allès, B., Boizot-Szantai, C., Soler, L.-G., Galan, P., … Kesse-Guyot, E. (2018). Comparing nutritional, economic, and environmental performances of diets according to their levels of greenhouse gas emissions. *Climatic Change*, *148*(1), 155–172. https://doi.org/10.1007/s10584-018-2195-1

Simopoulos, A. P., Bourne, P. G., & Faergeman, O. (2013). Bellagio Report on Healthy Agriculture, Healthy Nutrition, Healthy People. *Lifestyle Genomics*, *6*(1), 34–42. https://doi.org/10.1159/000346833

Song, G., Gao, X., Fullana-i-Palmer, P., Lv, D., Zhu, Z., Wang, Y., & Bayer, L. B. (2019). Shift from feeding to sustainably nourishing urban China: A crossing-disciplinary methodology for global environment-food-health nexus. *Science of The Total Environment*, *647*, 716–724. https://doi.org/10.1016/j.scitotenv.2018.08.040

Wood, S. A. (2018). Nutritional functional trait diversity of crops in south-eastern Senegal. *Journal of Applied Ecology*, *55*(1), 81–91. https://doi.org/10.1111/1365-2664.13026

Zech, K. M., & Schneider, U. A. (2019). Technical biofuel production and GHG mitigation potentials through healthy diets in the EU. *Agricultural Systems*, *168*, 27–35. https://doi.org/10.1016/j.agsy.2018.10.004

5. Chapter 3: Identification, comparison, and analysis of hypotheses in systematic review

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5.1 Abstract

For any given system of variables, such as those relating biodiversity, environment, and ecosystem processes, we can propose alternative hypotheses about the effects observed in nature and in experiments. Identifying those hypotheses in the literature that are actually comparable is often hard to achieve for complex ecological systems. In this study, we propose a method to identify, compare and analyze hypotheses for a complex system, using tools from quantitative review and statistics.

Our method consists of four steps: a systematic literature search for study selection, the identification of hypotheses through "backwards inference" from the original statistical analyses, the elimination of additional variables where experimental designs allow for it without altering the relation between remaining variables, and classification of compatible hypotheses into groups suitable for quantitative analysis. We provide a detailed case study of a system consisting of the relationships between biodiversity, productivity, light and nutrients.

In our case study, we found 760 initial papers, out of which 74 (123 independent studies) passed our selection criteria. From these, we identified 34 different hypotheses that were reduced to 15 when eliminating additional variables. Only five of them had been considered in more than one study. We found substantial differences between proposed hypotheses in terms of causality, with more intricate hypotheses - that would presumably better represent the higher complexity of the natural system - having been tested only a handful of times. Additionally, we recorded features that would be of relevance for a quantitative analysis (e.g., reported effect and study sizes, data availability, ecosystem type, etc.).

Our method allows for an accurate depiction of the number of times that compatible hypotheses have been tested. This is particularly valuable to evaluate whether it is possible or not to proceed with a rigorous quantitative review that can produce unbiased and robust statistical results. Moreover, our method facilitates the identification of knowledge gaps and mismatches between hypotheses, study designs and statistical tests in a given area of research.

Keywords: biodiversity, hypothesis, light, nutrients, productivity, systematic-review

5.2 Introduction

"Separate from the steps of assumption and definition, is the problem of research strategy: how best to choose hypotheses and how best to test them."

Hilborn and Stearns 1982

Reviews are fundamental to ecology, allowing for the detection of patterns in responses of groups of organisms and ecosystems to natural phenomena. Of all existing types of reviews, meta-analysis has proven to be a good quantitative approach to increase the statistical power available to test a hypothesis (Arnqvist & Wooster, 1995). Originally developed for medicine, meta-analysis has seen a rise in importance as a tool for quantitative review in ecology over the past 20 years (Koricheva *et al.,* 2013). Meta-analysis helps to overcome some of the shortcomings of traditional reviews, but some constraints still remain, including bias in the selection of studies and poor methodology in original studies (Gates, 2002; Head *et al.,* 2015; Morrissey, 2016).

One of the recurrent issues with research syntheses in ecology is the use of studies with somewhat distantly related hypotheses in the same analysis, for example to compare effects of global change drivers or systems across different temporal and spatial scales (e.g., Yuan *et al.*, 2017). It is indeed possible to perform a synthesis with a pool of heterogeneous studies, even with meta-analysis, when the aim is to reach broad generalizations (Hillebrand & Cardinale, 2010; Koricheva *et al.*, 2013). However, it is well stated in methodological synthesis papers that the source of the heterogeneity should be in the population of studies rather than in the hypotheses tested in these (Gurevitch *et al.,* 2018; Koricheva, Gurevitch & Mengersen, 2013). This is easier to achieve in medical sciences, where not only studies are more homogeneous (because designs are usually well-controlled interventions) but also easier to group according to a coherent common hypothesis than in ecology (Roberts *et al.,* 2006; Stewart & Schmid, 2015). Few quantitative reviews in ecology actually state the number of questions and hypotheses to be reviewed within the pool of studies used (but see for an example Balvanera *et al.* 2006 or Cardinale *et al.* 2009).

The distance allowed between working hypotheses to be pooled together for a data synthesis is decided together with inclusion criteria for paper selection. Pooling together studies whose original working hypotheses only slightly relate might hinder the biological interpretation of results (e.g., Mittelbach *et al.*, 2001 as evaluated by Whittaker & Heegaard, 2003). The fact that two hypotheses may be looking into the same ecological variables is not sufficient for them to be comparable statistically through meta-analysis: the direction of tested effects ("causality"), whether correlations or causal relationships were the focus of the original study designs, or differences in the hypothesized shape of a relationship could still preclude the use of them in the same meta-analysis. Naturally, the temporal and spatial scales at which relations between variables are assessed and the relevant characteristics of the population of studies (ecosystem type, life history traits, functional traits, ecological relationships, others) can be treated as explanatory variables for the heterogeneity of effects observed, in a formal meta-analysis.

Synthesis papers are usually widely read in the scientific community, sometimes even more than the original studies used to perform them (Pautasso, 2013). Therefore, loosely-based conclusions that may represent a trend rather than a confirmed effect can lead to confusion rather than help elucidate natural phenomena, if they are inappropriately interpreted as statistically robust and evidence-based. In order to avoid selecting studies that only support their hypothesis of preference, researchers must decide about the inclusion of a study based on its methods and not on its results (Gates, 2002). This concept could be taken further, into identifying hypotheses tested in original studies based on their statistical analysis, rather than on the verbal formulation of hypotheses or conclusions (even though, ideally, there should be no differences between the two approaches). For example, one-sided verbal hypotheses may be evaluated with a two-sided statistical test, yielding lower statistical power to detect effects, which may then not be reported as different from zero.

There are a number of papers and books that describe methodologies for quantitative reviews in ecology (Borenstein, 2009; Gates, 2002; Hedges *et al.,* 1999; Koricheva *et al.*, 2013; Nakagawa & Cuthill, 2007; Osenberg *et al.,* 1999). However, to our knowledge, none of them explicitly highlights the importance of the hypotheses tested in original papers being comparable, let alone proposes a threshold of compatibility or a systematic way of identifying and notating these hypotheses prior to performing a review with them. The abundance of quantitative reviews in ecology that are being performed by collating primary studies based on broadly related hypotheses (e.g., Hooper *et al.*, 2012), suggests that these are far from trivial tasks.

In the present study, we propose a method to identify compatible hypotheses that have been tested in a given literature pool. This method can be performed as a standalone to have a better comprehension of the state of the art in an area of knowledge, to identify plausible models to test over a given dataset, or, most likely, to be applied during the search of literature for data synthesis, particularly within ecology. We describe this method as applied to a case study.

5.3 Case study: resource competition, diversity and productivity in plant communities

Few questions interest community ecologists as much as why and how do species coexist. The “Hutchinsonian demon”, a species capable of always outcompeting the rest in every situation, cannot exist given the trade-offs in species capabilities and life-history traits and the changing environmental conditions in time and space (Kneitel & Chase, 2003). These trade-offs are not always easy to identify. Moreover, once identified, it might not be straightforward to quantify their relative role in determining the community structure, composition and function derived from them, since multifactorial experiments are more challenging than experiments manipulating a single factor (Hilborn & Stearns, 1982). A particular example of such a system can be found in plant communities, which are governed by a number of known variables: nutrient availability, light availability, number and composition of species, productivity, temperature and soil pH, among others. Numerous studies have performed single factor studies between pairs of variables within this system, with species richness and productivity having been a particularly controversial relationship (Cardinale *et al.,* 2009; Tilman *et al.*, 1997). Given the complexity of the system, few studies have accounted for numerous factors simultaneously and only recently have integrative models helped to reduce controversy (Grace *et al.*, 2016).

If we look at the system in the light of competition theory, we have: a) biotic factors (plants), that compete for b) resources (light, nutrients and water being the main ones), under a number of conditions generated by c) environmental variables such as space, time, temperature, soil pH, presence of grazers and disturbance. From single-factor experiments and comparative observational studies it is well established that there is a decline in plant diversity with nutrient addition (Bradford *et al.,* 2005; Gough *et al.,* 2000; Hillebrand, 2003; Tilman, 1987; Yang *et al.*, 2011). However, the mechanistic underpinnings remain a subject of debate because several non-exclusive mechanisms have been found to be at least partially responsible for observed outcomes, like increased competition for light (e.g., Schmid, 1989; Tilman, 1987), functional trait-specific mechanisms (e.g., Pennings *et al.*, 2005; Suding *et al.*, 2005), abundance mechanisms (e.g., Suding *et al.*, 2005), shifts in responses over time (e.g., Gross, Mittelbach, & Reynolds, 2005), and mycorrhizal interactions (e.g., Liu *et al.*, 2012).

Recent studies intended to shed light on the first of these mechanisms: the competition for nutrients belowground and competition for light aboveground, and their relation with biodiversity (e.g., species richness) and biomass production (DeMalach *et al.,* 2016; Harpole *et al.,* 2016; DeMalach & Kadmon, 2017; Harpole *et al.*, 2017). Their system of study, with all possible causal effects between the four study variables, is represented in Figure 5.1. These studies broadly dwell in a dichotomy between two frameworks: the niche dimensionality theory (Harpole *et al.*, 2016, 2017; Kaspari & Powers, 2016), and asymmetric light competition theory (DeMalach *et al.*, 2016; DeMalach *et al.,* 2017). Although these frameworks are not mutually exclusive, the focus of debate seemed to be whether one or the other framework was "sufficient" to explain diversity declines.

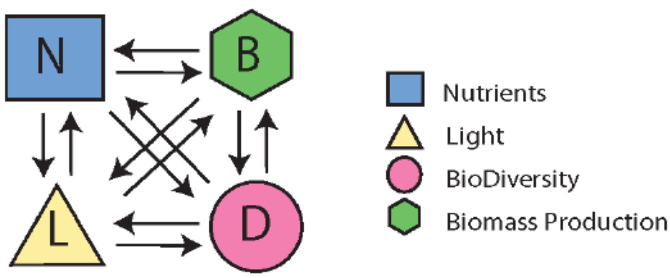

Fig. 5.1: Network diagram of all possible effects (arrows) between the four main variables of interest on plant competition for resources.

A possible way to measure the relative strength of the effects of nitrogen and light availability, and of the biodiversity and biomass production effects that could be simultaneously present, would be through a quantitative synthesis of the literature.

There are six interactions each with three possibilities (two directions or missing). Thus, there could be a maximum of 729 (3^6) hypotheses, not allowing arrows in both directions for a single interaction. But which of those have been actually proposed and tested for this system? Numerous syntheses have been done on the interaction between biodiversity and community productivity (Balvanera *et al.*, 2006; Cardinale *et al.*, 2007), but to our knowledge, none has included also interactions with nutrients and light in the same analysis. A prerequisite would be a sufficient amount of original studies testing the strength of all effects between these variables together. In the absence of an updated review on all hypotheses tested so far in the literature for this system, we applied our method for identifying and comparing those hypotheses that could be included in a quantitative analysis in the future.

5.4 Materials and methods

We propose a method for identification and comparison of hypotheses about the workings of complex natural systems, using the system described in Figure 1 as a case study. The method consists of four steps: a) study selection, b) hypothesis identification in the original study, c) elimination of additional variables, and d) grouping of compatible hypotheses (Fig. 5.2). With the hypothesis groups obtained from this method, we carried out a number of additional analyses (e).

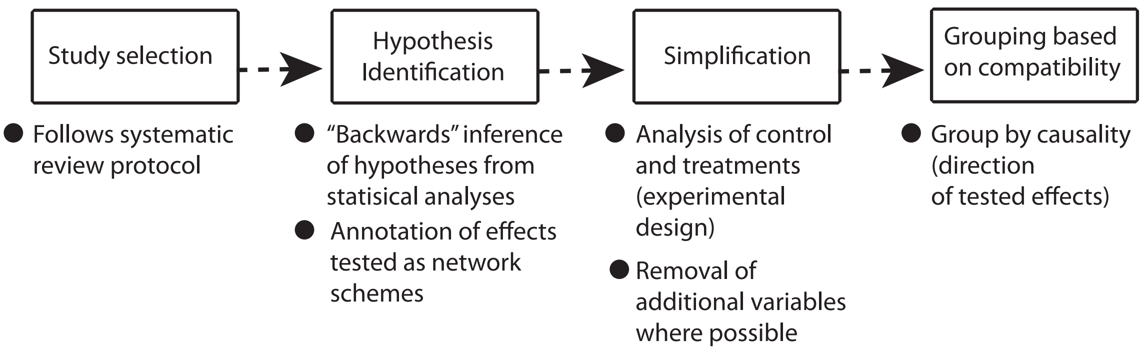

Fig. 5.2: Summary of method for hypothesis identification, comparison and analysis

5.4.1) Application of the method by steps

1) Study selection

First, we defined the variables of interest to establish the key terms we would look for and the scope of the quantitative review:

- *Nutrients:* amount of a particular nutrient, the number of different nutrients or their spatial disposition, which influence their availability in the soil. Any chemical element, in particular nitrogen and phosphorous, typically measured in amount of chemical element per area, per time.
- *Light:* refers to the amount or angle of light that penetrates the canopy. Light should have been measured on top of the canopy and under it, typically as photosynthetically active radiation (PAR).
- *Productivity or Biomass production:* refers to the mass of all the plants competing directly for measured resources, typically measured as aboveground dry weight produced after a given period of time.
- *Biodiversity:* Refers to the diversity of species in the plant community, typically measured as species richness, evenness, Shannon index or other diversity indices.

We developed a search strategy and protocol for literature acquisition through systematic review (Appendix 1). The search engines “Web of Science” and “Scopus” were used, by browsing in the title, abstract and keywords of papers for the following terms:

((fertilization or nutrient or nitrogen or phosphorus) and (light or shad$ or PAR) and (biodiversity or "biological diversity" or richness or evenness) and (biomass or productivity)).

Entries available online were considered for all years up to January 2018, when the last search was performed. Additional papers were included based on a screening of the results by external experts in community ecology and references considered relevant from all screened papers (Fig. 5.3).

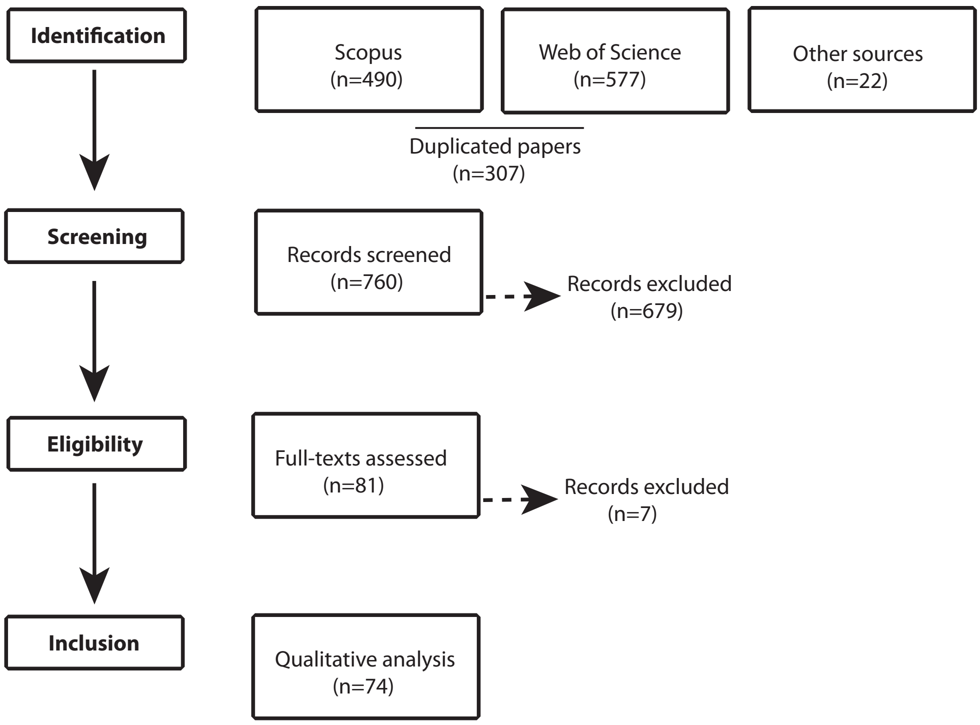

Fig. 5.3: Flow Diagram showing flow of information during the different phases of literature search.

After merging duplicated papers from the two databases, all resulting entries went through a first screening of abstract and methods sections. We selected for full-text review those papers that had quantified all four main variables of interest (nutrient, light, biomass and diversity). We rejected papers that had not measured at least one of these four variables, and theoretical or modeling-only studies. From all full-text reviewed papers, we extracted information that could serve to formulate the proposed hypothesis as a network (effect and response variables, covariates) and concrete information on experimental design (type of organisms, ecosystem type, measurements and units, number of replicates, etc.). We rejected studies that on a more detailed analysis did not conform with the criteria previously stated (measuring all four variables of interest), that lacked variation in explanatory variables, that had taken measurements which were deemed not comparable with the rest or in which measurements were not done for the main study organisms. The remaining 74 studies were included in the further analysis (Suppl. Mat. Appendix 2).

2) Hypotheses identification and notation

When performing an experiment, most studies state a null hypothesis and then compute a statistical test in order to reject or not reject it based on obtained data (Sokal & Rohlf, 2013). In order to identify the hypotheses proposed for our system in the literature, we did this backwards: we looked into the statistical tests performed by authors and translated them into network diagrams that show the actual hypothesis that had been tested, as derived from the analysis. Hypothetical systems of causality that were mentioned as plausible in other sections of the paper but that were not tested statistically were not included in our diagrams.

For example, Weilhoefer *et al.* (2017) performed a fertilization treatment (phosphorous and nitrogen addition) within a low-marsh zone. They measured responses in plant height, biomass, cover, abundance and richness, as well as light levels above and below the canopy. They performed an ANOVA analysis to examine the differences in these measurements before and after the fertilization treatment. Figure 4a shows the network diagram of the hypothesis tested in this paper, as we could interpret from this information. Although both in the introduction and in the discussion, Weilhoefer *et al.* 2017 mention that the decrease in light may have been a result of increased biomass, this indirect path is not included in our interpretation, given that this is not tested with the statistical analysis performed by them.

Several studies had performed path analysis and other statistical procedures that actually allowed them to test for hypothesized indirect effects and feedbacks between variables. For example, Cardinale *et al.* (2009) used a large dataset of phytoplankton species richness, algal biomass, total nutrient content (nitrogen and phosphorous) and light, among other environmental variables, from 492 lakes in Norway. To actually test their multivariate hypothesis, they used Structural Equations Model (SEM), and themselves structured their hypothesis as shown in Figure 5.4b. In this case, we could use their SEM network directly as a representation of their hypothesis. Note that here we have to assume that the SEM was stated a priori, because otherwise the hypothesis would have been fitted to the data rather than the other way around.

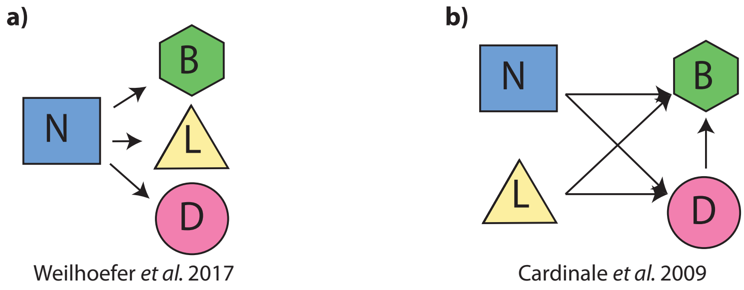

Fig. 5.4: Hypotheses for a) Weilhoefer *et al.* 2017 and b) Cardinale *et al.* 2009, as we could interpret based on methods and statistics.

Several papers had analyzed their observational data by fitting effects of co-variates *a posteriori*, therefore violating the rule that causal effects should be stated a priori. For example, Longhi & Beisner (2010) performed an observational study in 45 lakes of Canada, looking for the response of phytoplankton diversity to environmental factors, among which was "nutrient concentration". Additionally, they measured proxies for biomass and light penetration, among other variables. They performed summary statistics of all parameters across lakes and a descriptive analysis of variation between geographical regions. ANCOVAs were performed to establish which parameter accounted for the greater variation in diversity. We determined that although useful to establish patterns between the variables, these analyses couldn't be translated into causal effects, even though they produce effect sizes using the correlational data. Hence, this type of studies was excluded from our hypothesis analysis.

3) Elimination of treatments with additional variables (simplification)

Many authors included in their analyses more variables than the four of our focus, such as amount of litter present, water availability, temperature, soil or water pH, etc. In order to remain true to the statistical tests performed by authors, and to evaluate which other variables were frequently included in empirical studies, we included them in the network diagrams analyses and proceeded to evaluate which hypotheses could be merged in spite of these additional variables being present.

We listed all hypotheses and looked for commonalities between them. First, we grouped all systems based on the direction of effects (causality) between our four main variables of interest (nutrient, biodiversity, light and biomass), regardless of other variables present. Then we determined which experimental design would allow the elimination of additional variables. This was only possible when the additional variables were orthogonal to the main variables, at least for a subset of the data that could then be selected. Typically, this was the case if there was a (control) treatment in which the additional variable had not been manipulated. We assumed that removing the information about the additional variable should not, *a priori,* alter the experimental design for the remaining, which would allow a valid quantitative effect for remaining effects. In these cases we removed additional variables, as shown in Fig 5.5.

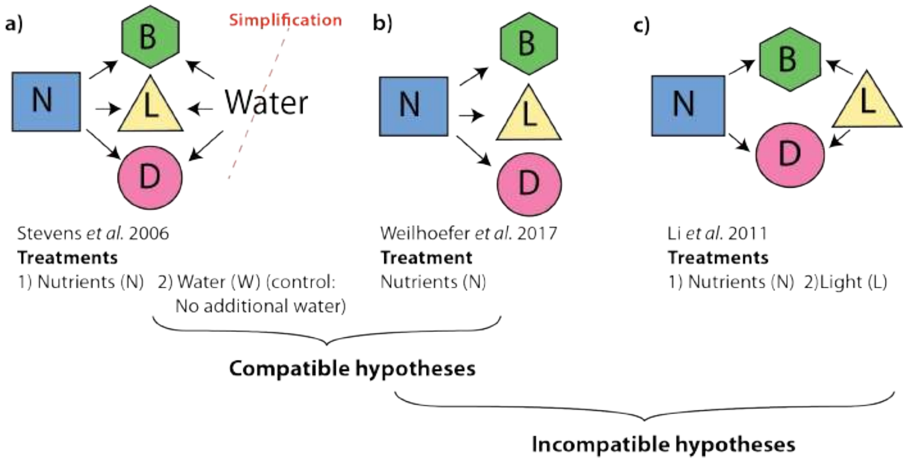

Fig. 5.5: Simplification of additional variables; the remaining hypotheses were classified as compatible or incompatible.

4) Grouping of compatible hypotheses

After this simplification, we defined **compatible systems** or **compatible hypotheses** as those that show the same network and direction of causality between all remaining variables. Hence, **incompatible systems** or **incompatible hypotheses** are those that differ in nodes, arrows and direction of arrows in their network representation (Fig 5.5). This admittedly strict compatibility rule greatly restricts the number of studies that can be included in a meta-analysis for a complex system such as the one we are interested in. For example, similar hypotheses such as Cardinale *et al.* 2009 and Li *et al.* 2011, are sufficiently different to preclude their use in the same analysis (Fig 5.6). We used this complex ecological system on purpose, to demonstrate the problems in finding compatible hypotheses in published papers for systems of more than 2 or 3 variables. After performing the simplification of additional variables, we tallied the number of incompatible systems in the literature.

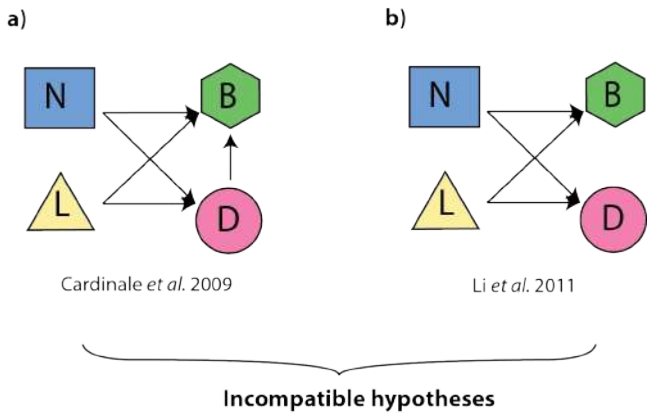

Fig. 5.6: Similar but incompatible hypotheses (note the arrow between biodiversity and biomass production).

In summary, through our method we eliminate additional variables only if they are treatment-type variables. There are two caveats to this method:

a) Some "additional" variables/co-variables cannot be removed (e.g., altitude), unless they would be "secretly" balanced (i.e. orthogonal) with the main variables,

b) It is not always the control of a study that remains after removing additional variables; it can also be another treatment level for which the additional variable is constant or orthogonal to the other main variables.

We dealt with these two caveats as follows:

a) Only studies where all additional variables explicitly accounted for by authors were identical were grouped as "compatible". We considered other potential additional variables that were not stated, as sources of heterogeneity that could be addressed during a meta-analysis.

b) We always took the control treatment in original studies, since the number of cases where other treatment levels could have been used, were negligible and to remain as faithful as possible to original experimental designs.

5.4.2) Additional analyses

Once all hypotheses were grouped based on compatibility, we addressed several issues of interest:

1) Type and number of reported effects

Each arrow in the networks of hypothesized causalities should be associated with an effect size; a quantitative measure of the magnitude of the effect (Koricheva *et al.*, 2013; Nakagawa & Cuthill, 2007). We calculated the percent of studies per hypothesis with sufficient data reported to readily calculate effect sizes. These are, e.g., standardized path coefficients, differences between arithmetic means (and errors) or indexes that could be mathematically derived from these (e.g., Hedges g). Reports of statistical significance *(p values)* are not sufficient for a quantitative integration.

2) Data availability

We report the percent of studies per hypothesis that have communicated the availability of data in online repositories (private or public) in their publication. No authors were contacted directly to enquire for availability of data.

3) Social network analysis of co-authors

We performed a network analysis of hypotheses and coauthors, in order to evaluate the associations between research groups working in this system. The analysis was performed as a bipartite network, using R Software (R Development Core Team, 2013). We looked in particular at the number of hypotheses tested by single authors.

5.5. Results

The list of 74 papers included in our analysis can be found in the Supplementary Information (Suppl. Mat. Appendix 2), broken down into the number of independent studies included in each paper (123 in total) and their corresponding hypothesis number (Suppl. Mat. Table S5.1). Ten of these papers were studies where the causality of effects was not clear, as they established correlations between variables without stating a direction. The exclusion of these ten papers is justified in our protocol (Suppl. Mat. Appendix 1). In the remaining 64 papers, we identified 34 different hypotheses that had been proposed for explaining interactions between nutrients, light, diversity, biomass and other environmental variables considered relevant for this system. The additional variables that were tested the most were the amount of litter present in the soil and the amount of vegetation cover (Suppl. Mat. Table S5.2).

The 34 hypotheses went through the elimination of additional variables, so as to compare only the direction of the interactions of the main system of interest. Figure 7 shows the 15 remaining incompatible hypotheses, from which the first 5 have been tested more than once (Fig 5.7a) in the literature and the rest only once (Fig 5.7b).

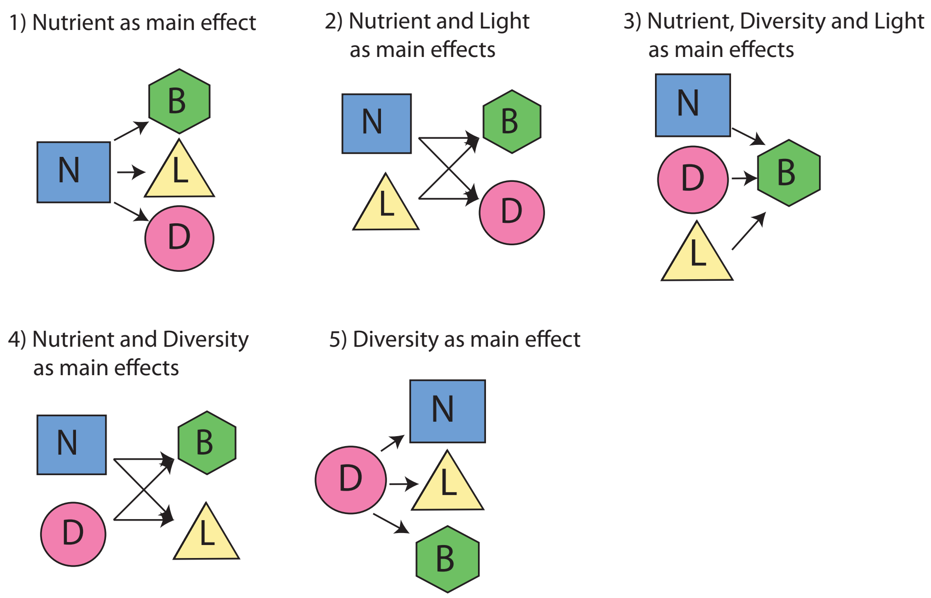

Fig 5.7a: Five different hypotheses tested multiple times in the literature.

Results show that most studies have tested how the addition or reduction of nutrient availability in the soil directly affects light penetration through the canopy, the amount of biomass and the species diversity of the plant community, regardless of potential interactions between these variables (Hypothesis 1). In second place, numerous studies manipulated both nutrient amount and light availability so that the direct effects of below- and aboveground competition on biomass and diversity could be assessed separately (Hypothesis 2; note that these studies also could include interactive effects of nutrients and light, which are not depicted in the diagrams in Fig. 5.7). In the rest of the hypotheses, diversity is always an explanatory variable and biomass is always a response variable whereas light and nutrient availability switch from explanatory to response variable (Hypotheses 3–5). According to Hypothesis 5, all changes are driven by diversity (Table 5.2).

Table 5.2: ID: Hypothesis ID; Co: number of compatible hypotheses, k: Number of studies, Ef: number of studies with effect sizes reported, Av: raw data availability and ecosystem of the most tested hypotheses (G: grassland, A: aquatic, T: tundra, W: wetland, F: forest).

ID	Co	k	Ef	Av	Ecosystem studied				
					G	A	T	W	F
1) Nutrients as effect	14	38	24	34%	95%	-	-	5%	-
2) Nutrients and Light as effects	6	19	11	0%	37%	26%	16%	-	5%
3) Nutrients, Diversity and Light as effects	2	7	3	0%	100%	-	-	-	-
4) Nutrients and Diversity as effects	2	2	0	0%	100%	-	-	-	-
5) Diversity as effect	1	10	8	100%	100%	-	-	-	-

Figure 5.7b shows the 10 hypotheses that were tested once in the literature and that could not be merged through elimination of additional variables with any other, meaning that it would not be possible to include them together in a meta-analysis using our rules for selecting studies.

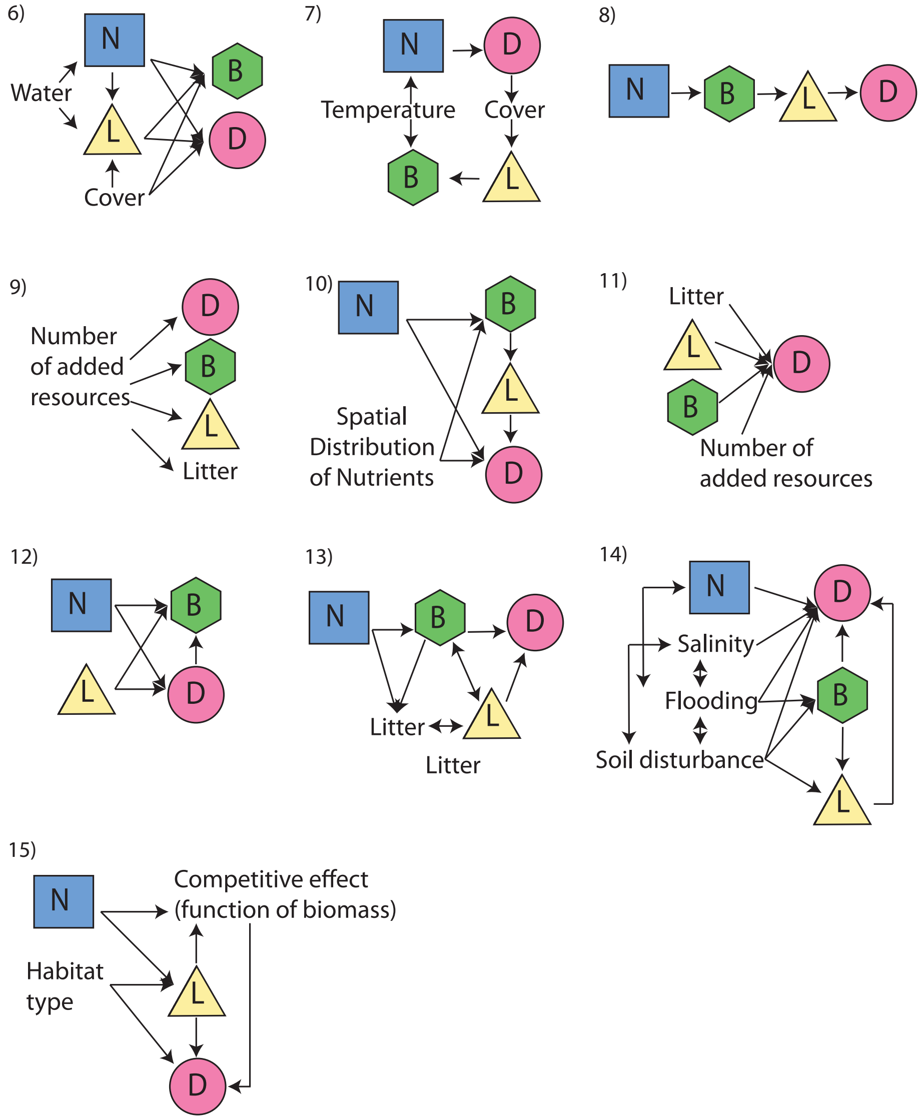

Fig. 5.7b: Ten hypotheses tested once in the literature.

If we would step outside of our method and use subsystems within the stated hypotheses, then it would be possible to get a higher number of effects per interaction, to be used in statistical analyses. For example, we could take one sensible hypothesis (e.g., hypothesis 12, Cardinale *et al.* 2009) and use the effects of all pairwise interactions found in all other hypotheses, regardless of compatibility. Figure 8 shows the number of effects that we would have available for each interaction in the diagram (see Suppl. Mat. Table S5.3 for details).

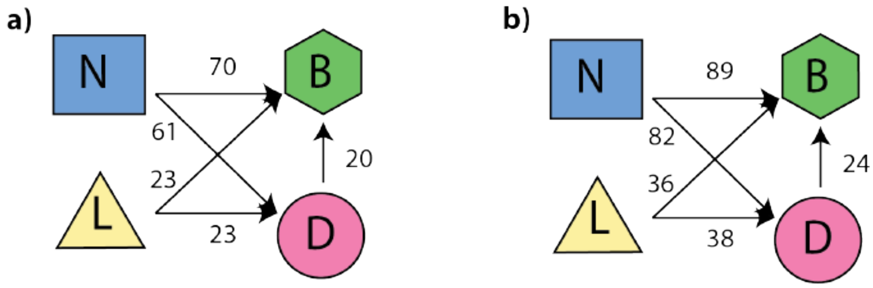

Fig. 5.8: Causal relationships from hypothesis 12, analyzed when pooling all hypotheses that had accounted for them, also those deemed incompatible according to our method. (a) Number of effect sizes reported, (b) Number of effect sizes reported plus studies that had studied those interactions but have not reported effect sizes (access to raw data would be required to use them).

An interesting future exercise would be to test the difference of performing a meta-analysis only with compatible hypotheses and another one for the same interactions but pooling effect sizes from incompatible hypotheses together (such as in Fig. 5.8). This would be a way of testing how the level of compatibility between hypotheses affects the overall results. However, this is currently not possible given that none of the hypotheses individually was tested enough times and not enough effect sizes had been reported (e.g., hypothesis 12 (figure 8) was tested once in the literature only).

The social network visualization revealed that 17 out of 243 coauthors have performed studies with three or more different hypotheses (reduced network Fig. 9, see complete network in Suppl. Mat. Fig. S5.2). Within these 17, the majority of authors tested three of the hypotheses (numbers 1, 8 and 9). Hypothesis 1 has been supported in numerous independent and disconnected studies, while Hypothesis 8 corresponds to only one integrative modeling paper with numerous authors, and Hypothesis 9 to a meta-analysis with numerous authors. Almost every author who has attempted several hypotheses has at some point supported Hypothesis 1.

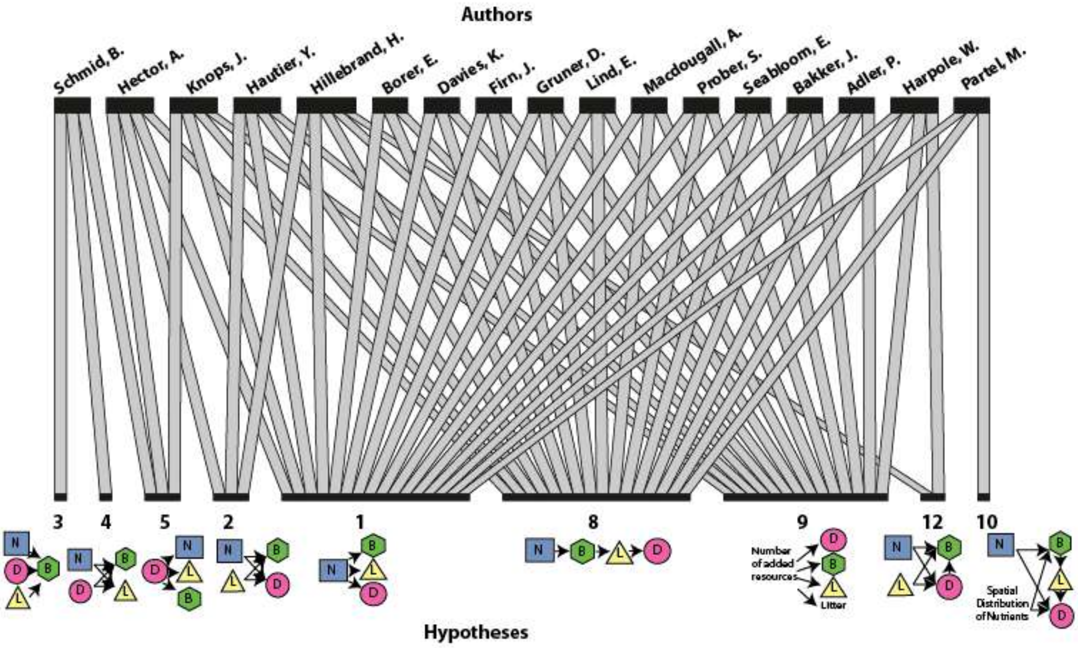

Fig. 5.9: Social network with authors participating in three or more hypotheses

5.6 Discussion

We propose a method for identifying and comparing current working hypotheses for a system of interest using a review of available literature, "backwards inference" from statistical analyses, elimination of additional variables, and grouping of hypotheses based on the hypothesized causal relationships. We believe the application of this method will be particularly useful in areas of ecology in which there is a current debate on which are the mechanisms responsible for already established relations between variables. Moreover, it would help in the detection of knowledge and data gaps in the literature, as well as the limitations of recurrent experimental design and statistical analyses.

In order to test this, we used the system of interactions between nutrients, light, diversity and productivity. Results show that although many hypotheses have been proposed to explain the causality between the variables of this system (more than 30), few of them have actually been tested repeatedly, even when reducing additional variables. This fact blurs the relevance of papers that advocate for one or another hypothesis in particular, as we see that there is actually not enough research done to support any of them, let alone to generalize to plant communities outside grassland ecosystems. Furthermore, the shortage of properly reported effect sizes, an issue that has been repeatedly denounced for many areas of ecology in the research synthesis literature (Gerstner *et al.*, 2017; Nakagawa & Poulin, 2012), hinders the possibility of performing quantitative synthesis like meta-analyses, which would be a great tool to directly measure the relative strength of the effects between variables.

Reductionist approaches in science are based on the presupposition that simple hypotheses need to be rejected first, followed by exploration of more complex ones (Hilborn & Stearns, 1982). Our findings for the case study seem to fit this statement, as the simplest hypotheses have been tested more times. The hypotheses that have considered feedbacks and indirect effects between variables have mostly been tested once and often only with Structural Equation Modeling (SEM), which uses a-priori hypothetical frameworks that are then fitted to covariance or correlation matrices, i.e. lack a rigorous experimental setting. When multiple explanatory variables are experimentally manipulated the system could become even more complex than depicted in our diagrams, because of the interactions between them, such that one arrow changes depending on the level of other variables. Despite these complications, we suggest that it is heuristically valuable applying a method of hypotheses classification as done here. It could also be useful to use an approach that reduces complex hypotheses to simpler ones that include only relevant aspects of the complexity of the system, while allowing feasible experimental designs (e.g., Heger *et al.*, 2013; Jeschke & Heger, 2011).

One of the major challenges for generalization in the research area of our case study is the over-representation of grassland as ecosystem type. It is possible that results between studies from grassland (and mostly with the same functional types of plants, i.e. grasses, legumes and non-leguminous herbs), will have more similar results than a set of studies carried out across multiple ecosystem types would have. This can be a source of bias on the overall results of a potential quantitative analysis (Gates, 2002), especially since at least some responses seem to be community-specific (e.g., Gough *et al.*, 2000).

Grouping hypotheses based on the causalities they suggest allowed us to depict the social network of co-authors based on their similarities. In our case study comparatively few authors out of the total have explored more than one hypothesis. This could be due to technical limitations of the places that they are working in or because they strongly support one hypothesis theoretically. Further studies could be performed with this social network structure in order to compare the number of hypotheses that authors have tested and their impact in the community (number of collaborations, citation indexes, others). These analyses exceed the present methodological paper.

Looking forward as a community, we think that these results should shift the debate from the importance of particular mechanisms, to a debate on 1) which are the most plausible and interesting hypotheses that we would like to test and compare, 2) which are the best plausible experimental designs to test them, and 3) which are the best statistical analyses that would allow us to clearly test each of the effects in the system and 4) how to report them in a synthesis-friendly way.

Our method allowed us to clearly identify all hypotheses in the relevant literature, compare them and group them in order to better visualize their complexity and the links between them. The advantage of this method against traditional reviews is that it avoids confounding tested hypothesis with information present in the theoretical background of the papers and with ad-hoc interpretations of results. We believe that this would be an interesting analysis in other controversial areas of ecology, such as to comprehend the effects of different elements on ecosystem multi-functionality, the effects of different agro-forestry managements on diversity or in invasive species ecology.

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Author contributions

M.A.P. performed the literature search, method design, application of the method to the case study, analysis and manuscript writing. B.S. assisted in applying the method, supervised the case study application and manuscript writing. O.L.P. participated in the analysis and manuscript writing. All authors were critically important in the interpretation of data from this study.

Data Accessibility

All data used in this study will be stored in KNB, public repository (https://knb.ecoinformatics.org/)-*urn:uuid:27c51c0f-81b6-4d37-9a3e-331bcbd14168*

5.7 References

Arnqvist, G., & Wooster, D. (1995). Meta-analysis: synthesizing research findings in ecology and evolution. *Trends Ecol Evol*, *10*.

Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J.-S., Nakashizuka, T., Raffaelli, D., & Schmid, B. (2006). Quantifying the evidence for biodiversity effects on ecosystem functioning and services: Biodiversity and ecosystem functioning/services. *Ecology Letters*, *9*(10), 1146–1156.

Borenstein, M. (2009). Effect size for continuous data. In H. Cooper, L. V. Hedges, & J. C. Valentine (Eds.), *The handbook of research synthesis and meta-analysis*. New York: Russell Sage Foundation.

Bradford, J. B., Lauenroth, W. K., & Burke, I. C. (2005). The impact of cropping on primary production in the U.S. Great Plains. *Ecology*, *86*(7), 1863–1872.

Cardinale, B. J., Hillebrand, H., Harpole, W. S., Gross, K., & Ptacnik, R. (2009). Separating the influence of resource 'availability' from resource 'imbalance' on productivity–diversity relationships. *Ecology Letters*, *12*(6), 475–487.

Cardinale, B. J., Wright, J. P., Cadotte, M. W., Carroll, I. T., Hector, A., Srivastava, D. S., … Weis, J. J. (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proceedings of the National Academy of Sciences*, *104*(46), 18123–18128.

DeMalach, N., & Kadmon, R. (2017). Light competition explains diversity decline better than niche dimensionality. *Functional Ecology*, *31*(9), 1834–1838.

DeMalach, N., Zaady, E., & Kadmon, R. (2017). Light asymmetry explains the effect of nutrient enrichment on grassland diversity. *Ecology Letters*, *20*(1), 60–69.

DeMalach, N., Zaady, E., Weiner, J., & Kadmon, R. (2016). Size asymmetry of resource competition and the structure of plant communities. *Journal of Ecology*, *104*(4), 899–910.

Gates, S. (2002). Review of methodology of quantitative reviews using meta-analysis in ecology. *Journal of Animal Ecology*, *71*(4), 547–557.

Gerstner, K., Moreno-Mateos, D., Gurevitch, J., Beckmann, M., Kambach, S., Jones, H. P., & Seppelt, R. (2017). Will your paper be used in a meta-analysis? Make the reach of your research broader and longer lasting. *Methods in Ecology and Evolution*, *8*(6), 777–784.

Gough, L., Shaver, G. R., Carroll, J., Royer, D. L., & Laundre, J. A. (2000). Vascular plant species richness in Alaskan arctic tundra: the importance of soil pH. *Journal of Ecology*, *88*(1), 54–66.

Grace, J. B., Anderson, T. M., Seabloom, E. W., Borer, E. T., Adler, P. B., Harpole, W. S., … Smith, M. D. (2016). Integrative modeling reveals mechanisms linking productivity and plant species richness. *Nature*, *529*(7586), 390–393.

Gross, K. L., Mittelbach, G. G., & Reynolds, H. L. (2005). Grassland invasibility and diversity: Responses to nutrients, seed input, and disturbance. *Ecology*, *86*(2), 476–486.

Gurevitch, J., Koricheva, J., Nakagawa, S., & Stewart, G. (2018). Meta-analysis and the science of research synthesis. *Nature*, *555*, 175.

Harpole, W. S., Sullivan, L. L., Lind, E. M., Firn, J., Adler, P. B., Borer, E. T., … Wragg, P. D. (2016). Addition of multiple limiting resources reduces grassland diversity. *Nature*, *537*(7618), 93–96.

Harpole, W.S., Sullivan, L. L., Lind, E. M., Firn, J., Adler, P. B., Borer, E. T., … Stevens, C. J. (2017). Out of the shadows: multiple nutrient limitations drive relationships among biomass, light and plant diversity. *Functional Ecology*.

Head, M. L., Holman, L., Lanfear, R., Kahn, A. T., & Jennions, M. D. (2015). The Extent and Consequences of P-Hacking in Science. *PLOS Biology*, *13*(3), e1002106.

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, *80*.

Hilborn, R., & Stearns, S. C. (1982). On inference in ecology and evolutionary biology: the problem of multiple causes. *Acta Biotheoretica*, *31*(3), 145–164.

Hillebrand, H. (2003). Opposing effects of grazing and nutrients on diversity. *Oikos*, *100*(3), 592–600. Retrieved from JSTOR.

Hillebrand, H., & Cardinale, B. J. (2010). A critique for meta-analyses and the productivity-diversity relationship. *Ecology*, *91*(9), 2545–2549.

Hooper, D. U., Adair, E. C., Cardinale, B. J., Byrnes, J. E. K., Hungate, B. A., Matulich, K. L., … O'Connor, M. I. (2012). A global synthesis reveals biodiversity loss as a major driver of ecosystem change. *Nature*, (486), 105–108.

Kaspari, M., & Powers, J. S. (2016). Biogeochemistry and Geographical Ecology: Embracing All Twenty-Five Elements Required to Build Organisms. *The American Naturalist*, *188*(S1), S62–S73.

Kneitel, J. M., & Chase, J. M. (2003). Trade-offs in community ecology: linking spatial scales and species coexistence. *Ecology Letters*, *7*(1), 69–80.

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). *Handbook of meta-analysis in ecology and evolution*.

Koricheva, J., Jennions, M. D., & Lau, J. (2013). Temporal trends in effect sizes: causes, detection and implications. In J. Koricheva & J. Gurevitch (Eds.), *Mengersen K, editors*. Princeton: Princeton University Press.

Liu, Y., Shi, G., Mao, L., Cheng, G., Jiang, S., Ma, X., … Feng, H. (2012). Direct and indirect influences of 8 yr of nitrogen and phosphorus fertilization on Glomeromycota in an alpine meadow ecosystem. *The New Phytologist*, *194*(2), 523–535.

Mittelbach, G. G., Steiner, C. F., Scheiner, S. M., Gross, K. L., Reynolds, H. L., Waide, R. B., … Gough, L. (2001). What is the observed relationship between species richness and productivity? *Ecology*, *82*(9), 2381–2396. https://doi.org/10.1890/0012-9658(2001)082[2381:WITORB]2.0.CO;2

Morrissey, M. (2016). Meta-analysis of magnitudes, differences, and variation in evolutionary parameters. *J Evol Biol*, *29*.

Nakagawa, S., & Cuthill, I. C. (2007). Effect size, confidence interval and statistical significance: a practical guide for biologists. *Biol Rev*, *82*.

Nakagawa, Shinichi, & Poulin, R. (2012). Meta-analytic insights into evolutionary ecology: an introduction and synthesis. *Evolutionary Ecology*, *26*(5), 1085–1099. https://doi.org/10.1007/s10682-012-9593-z

Osenberg, C. W., Sarnelle, O., Cooper, S. D., & Holt, R. D. (1999). Resolving ecological questions through meta-analysis: goals, metrics and models. *Ecology*, *80*(4), 1105–1117.

Pautasso, M. (2013). Ten Simple Rules for Writing a Literature Review. *PLOS Computational Biology*, *9*(7), e1003149.

Pennings, S. C., Clark, C. M., Cleland, E. E., Collins, S. L., Gough, L., Gross, K. L., … Suding, K. N. (2005). Do Individual Plant Species Show Predictable Responses to Nitrogen Addition across Multiple Experiments? *Oikos*, *110*(3), 547–555.

R Development Core Team. (2013). *R: A language and environment for statistical computing.* Retrieved from http://www.R-project.org

Roberts, P. D., Stewart, G. B., & Pullin, A. S. (2006). Are review articles a reliable source of evidence to support conservation and environmental management? A comparison with medicine. *Biological Conservation*.

Schmid, B. (1989). Tilman, D. 1988. Plant Strategies and the Dynamics and Structure of Plant Communities. Monographs in Population Biology 26. Princeton University Press, Princeton, *Journal of Evolutionary Biology*, *2*(5), 388–390.

Sokal, R., & Rohlf, F. (2013). *Biometry : the principles and practice of statistics in biological research / Robert R. Sokal and F. James Rohlf*.

Stewart, G. B., & Schmid, C. H. (2015). Lessons from meta-analysis in ecology and evolution: the need for trans-disciplinary evidence synthesis methodologies. *Res Synth Methods*, *6*.

Suding, K. N., Collins, S. L., Gough, L., Clark, C., Cleland, E. E., Gross, K. L., … Pennings, S. (2005). Functional- and abundance-based mechanisms explain diversity loss due to N fertilization. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(12), 4387.

Tilman, D. (1987). Secondary Succession and the Pattern of Plant Dominance Along Experimental Nitrogen Gradients. *Ecological Monographs*, *57*(3), 190–214.

Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., & Siemann, E. (1997). The Influence of Functional Diversity and Composition on Ecosystem Processes. *Science*, *277*(5330), 1300.

Whittaker, R. J., & Heegaard, E. (2003). What is the observed relationship between species richness and productivity? Comment. *Ecology*, *84*(12), 3384–3390.

Yang, H., Li, Y., Wu, M., Zhang, Z., Li, L., & Wan, S. (2011). Plant community responses to nitrogen addition and increased precipitation: the importance of water availability and species traits. *Global Change Biology*, *17*(9), 2936–2944.

Yuan, Z., Jiao, F., Shi, X., Sardans, J., Maestre, F. T., Delgado-Baquerizo, M., … Peñuelas, J. (2017). Experimental and observational studies find contrasting responses of soil nutrients to climate change. *ELife*, *6*, e23255.

5.8 Supplementary material

Appendix 1: Protocol for study selection

Databases and additional sources for literature search

- Web of Science Core collection
- Scopus
- Personal communication with experts in Community Ecology

Publication years: All years until January 2018

Search strategy: keywords with the variables of interest

- *Entry used: ((fertilization or nutrient or nitrogen or phosphorus) and (light or shad$ or PAR) and (biodiversity or "biological diversity" or richness or evenness) and (biomass or productivity)).*

Limits applied to the search

- Search in Title, Abstract and Keywords ("Topic" in Web of Science Core collection)
- All document types (article, review, book, thesis, data papers, etc.).
- All access types (open access or restricted)
- All languages (but only those in English, French, Spanish, German and Chinese were considered)

Screening process - Exclusion and inclusion criteria

- Computational modeling studies without field or laboratory data were excluded.
- Experimental and survey/observational studies were included.
- The methods section must have stated that at least the 4 main variables of interest (nutrients, light, diversity and biomass) were measured in field or lab, in any measurement type and expressed in any unit (e.g.: for "nutrient" we considered "amount", "spatial distribution in soil", "availability" and "intake" all valid for further revision).
- Late exclusion criteria: It must be possible to extract a working hypothesis from the statistical analysis of each paper, that implies causality between studied variables. This causality should have been tested explicitly through statistical analyses in the original paper and not only stated in other sections of the paper

or deduced after the data had been analyzed. In the case of papers where contradicting hypotheses have been stated and tested, only the one tested statistically should be considered. Those papers where there is no causal relation tested between the variables of interest cannot be included in the hypothesis identification analysis. However, they should still be included in the "useful" remaining literature pool, as they had collected data that could be re-analyzed with other statistical techniques (e.g.: SEM), or as part of a primary data research synthesis.

Data to be extracted

- From results and analyses section: Hypothesis tested statistically of the relation between the variables of interest for this system.
- Number and type of effect sizes reported or with sufficient data to be calculated, for each interaction in the hypothesis tested.
- Availability of raw data in public repositories (open or upon request).
- Additional variables considered relevant for this system by authors (e.g.: temperature).
- Measurement types and units used by authors.
- Ecosystem and species studied.
- All the names of authors involved in proposing or analyzing the hypothesis (for social network analysis).

Summary of data to be reported

- Hypotheses expressed as causal loop diagrams, with the correspondent type of effect size reported
- List of measurements and units used for each variable of interest
- List of additional variables used in the literature for this system
- Percent of studies that worked in each ecosystem
- Percent of studies that reported effect sizes or enough data to calculate them for all interactions in their hypothesis.
- Percent of studies with available raw data in public repositories
- Fidelity to a hypothesis and connection between researchers, as a social network

Appendix 2: References for papers used in the case study

Baer, S. G., Blair, J. M., Collins, S. L., & Knapp, A. K. (2003). Soil resources regulate productivity and diversity in newly established tallgrass prairie. *Ecology*, *84*(3), 724–735. https://doi.org/10.1890/0012-9658(2003)084[0724:SRRPAD]2.0.CO;2

Barnett, A., & Beisner, B. E. (2007). Zooplankton biodiversity and lake trophic state: Explanations invoking resource abundance and distribution. *Ecology*, *88*(7), 1675–1686. https://doi.org/10.1890/06-1056.1

Becker, V., Caputo, L., Ordóñez, J., Marcé, R., Armengol, J., Crossetti, L. O., & Huszar, V. L. M. (2010). Driving factors of the phytoplankton functional groups in a deep Mediterranean reservoir. *Water Research*, *44*(11), 3345–3354. https://doi.org/10.1016/j.watres.2010.03.018

Borer, E. T., Seabloom, E. W., Gruner, D. S., Harpole, W. S., Hillebrand, H., Lind, E. M., … Yang, L. H. (2014). Herbivores and nutrients control grassland plant diversity via light limitation. *Nature*, *508*(7497), 517-+. https://doi.org/10.1038/nature13144

Bymers, L., Glenn, E. P., Nelson, S. G., & Fitzsimmons, K. (2005). Diversity and biomass dynamics of marine algae in biosphere II's tropical reef macrocosm. *Ecological Engineering*, *25*(4), 442–456. https://doi.org/10.1016/j.ecoleng.2005.07.014

Cardinale, B. J., Hillebrand, H., Harpole, W. S., Gross, K., & Ptacnik, R. (2009). Separating the influence of resource 'availability' from resource 'imbalance' on productivity–diversity relationships. *Ecology Letters*, *12*(6), 475–487. https://doi.org/10.1111/j.1461-0248.2009.01317.x

Chapin, F., Shaver, G., Giblin, A., Nadelhodder, K., & Laundre, J. (1995). Responses of artic tundra to experimental and observed changes in climate. *Ecology*, *76*(3), 694–711.

Chiarucci, A., Alongi, C., & Wilson, J. B. (2004). Competitive exclusion and the No-Interaction model operate simultaneously in microcosm plant communities. *Journal of Vegetation Science*, *15*(6), 789–796. https://doi.org/10.1111/j.1654-1103.2004.tb02322.x

Clark, C. M., & Tilman, D. (2010). Recovery of plant diversity following N cessation: effects of recruitment, litter, and elevated N cycling. *Ecology*, *91*(12), 3620–3630. https://doi.org/10.1890/09-1268.1

Crossetti, L. O., Bicudo, D. C., Bicudo, C. E. M., & Bini, L. M. (2008). Phytoplankton biodiversity changes in a shallow tropical reservoir during the hypertrophication process. *Brazilian Journal of Biology*, *68*(4), 1061–1067.

DeMalach, N., & Kadmon, R. (2017). Light competition explains diversity decline better than niche dimensionality. *Functional Ecology*, *31*(9), 1834–1838. https://doi.org/10.1111/1365-2435.12841

DeMalach, N., Zaady, E., & Kadmon, R. (2017). Light asymmetry explains the effect of nutrient enrichment on grassland diversity. *Ecology Letters*, *20*(1), 60–69. https://doi.org/10.1111/ele.12706

Dickson, T. L., & Foster, B. L. (2011). Fertilization decreases plant biodiversity even when light is not limiting. *Ecology Letters*, *14*(4), 380–388. https://doi.org/10.1111/j.1461-0248.2011.01599.x

Dickson, T. L., Mittelbach, G. G., Reynolds, H. L., & Gross, K. L. (2014). Height and clonality traits determine plant community responses to fertilization. *Ecology*, *95*(9), 2443–2452.

Eek, L., & Zobel, K. (1997). Effects of additional illumination and fertilization on seasonal changes in fine-scale grassland community structure. *Journal of Vegetation Science*, *8*(2), 225–234. https://doi.org/10.2307/3237351

Eriksson, B. K., Rubach, A., & Hillebrand, H. (2006). Biotic habitat complexity controls species diversity and nutrient effects on net biomass production. *Ecology*, *87*(1), 246–254. https://doi.org/10.1890/05-0090

Fessel, C., Meier, I. C., & Leuschner, C. (2016). Relationship between species diversity, biomass and light transmittance in temperate semi-natural grasslands: is productivity enhanced by complementary light capture? *Journal of Vegetation Science*, *27*(1), 144–155. https://doi.org/10.1111/jvs.12326

Foster, B. L., & Gross, K. L. (1998). Species richness in a successional grassland: Effects of nitrogen enrichment and plant litter. *Ecology*, *79*(8), 2593–2602. https://doi.org/10.1890/0012-9658(1998)079[2593:SRIASG]2.0.CO;2

Fridley, J. D. (2003). Diversity effects on production in different light and fertility environments: an experiment with communities of annual plants. *Journal of Ecology*, *91*(3), 396–406. https://doi.org/10.1046/j.1365-2745.2003.00775.x

Gazol, A., Tamme, R., Price, J. N., Hiiesalu, I., Laanisto, L., & Paertel, M. (2013). A negative heterogeneity-diversity relationship found in experimental grassland communities. *Oecologia*, *173*(2), 545–555. https://doi.org/10.1007/s00442-013-2623-x

Gendron, F., & Wilson, S. D. (2007). Responses to fertility and disturbance in a low-diversity grassland. *Plant Ecology*, *191*(2), 199–207. https://doi.org/10.1007/s11258-006-9237-x

Gooden, B., & French, K. (2015). Impacts of alien plant invasion on native plant communities are mediated by functional identity of resident species, not resource availability. *Oikos*, *124*(3), 298–306. https://doi.org/10.1111/oik.01724

Gough, L., Wookey, P. A., & Shaver, G. R. (2002). Dry heath arctic tundra responses to long-term nutrient and light manipulation. *Arctic, Antarctic, and Alpine Research*, *34*(2), 211–218. Retrieved from Scopus.

Grace, J. B., Anderson, T. M., Seabloom, E. W., Borer, E. T., Adler, P. B., Harpole, W. S., … Smith, M. D. (2016). Integrative modeling reveals mechanisms linking productivity and plant species richness. *Nature*, *529*(7586), 390–393.

Grace, J. B., & Pugesek, B. H. (1997). A Structural Equation Model of Plant Species Richness and Its Application to a Coastal Wetland. *The American Naturalist*, *149*(3), 436–460. https://doi.org/10.1086/285999

Gross, K. L., Mittelbach, G. G., & Reynolds, H. L. (2005). Grassland invasibility and diversity: Responses to nutrients, seed input, and disturbance. *Ecology*, *86*(2), 476–486. Retrieved from Scopus.

Gross, Katherine L., & Mittelbach, G. G. (2017). Negative effects of fertilization on grassland species richness are stronger when tall clonal species are present. *Folia Geobotanica*, *52*(3), 401–409. https://doi.org/10.1007/s12224-017-9300-5

Han, Z., & Cui, B. (2016). Performance of macrophyte indicators to eutrophication pressure in ponds. *Ecological Engineering*, *96*, 8–19. https://doi.org/10.1016/j.ecoleng.2015.10.019

Harpole, W. Stanley, Sullivan, L. L., Lind, E. M., Firn, J., Adler, P. B., Borer, E. T., … Wragg, P. D. (2016). Addition of multiple limiting resources reduces grassland diversity. *Nature*, *537*(7618), 93–96. https://doi.org/10.1038/nature19324

Harpole, W.S., & et. al. (2016). Addition of multiple limiting resources reduces grassland diversity. *Nature*.

Harpole, W.S., Sullivan, L. L., Lind, E. M., Firn, J., Adler, P. B., Borer, E. T., … Stevens, C. J. (2017). Out of the shadows: multiple nutrient limitations drive relationships among biomass, light and plant diversity. *Functional Ecology*, *31*(9), 1839–1846. https://doi.org/10.1111/1365-2435.12967

Hautier, Y., Niklaus, P. A., & Hector, A. (2009). Competition for Light Causes Plant Biodiversity Loss After Eutrophication. *Science*, *324*(5927), 636–638. https://doi.org/10.1126/science.1169640

Huber, R. (1994). Changes in plant species richness in a calcareous grassland following changes in environmental conditions. *Folia Geobotanica et Phytotaxonomica*, *29*(4), 469–482. https://doi.org/10.1007/BF02883145

Jarchow, M. E., & Liebman, M. (2012). Nutrient enrichment reduces complementarity and increases priority effects in prairies managed for bioenergy. *Biomass & Bioenergy*, *36*, 381–389. https://doi.org/10.1016/j.biombioe.2011.11.010

Klanderud, K., & Totland, O. (2008). Diversity-Stability Relationships of an Alpine Plant Community under Simulated Environmental Change. *Arctic Antarctic and Alpine Research*, *40*(4), 679–684. https://doi.org/10.1657/1523-0430(07-075)

Kleijn, D., & Van Der Voort, L. A. C. (1997). Conservation headlands for rare arable weeds: The effects of fertilizer application and light penetration on plant growth. *Biological Conservation*, *81*(1–2), 57–67. https://doi.org/10.1016/S0006-3207(96)00153-X

Lamb, E. G. (2008). Direct and indirect control of grassland community structure by litter, resources, and biomass. *Ecology*, *89*(1), 216–225. https://doi.org/10.1890/07-0393.1

Li, L.-J., Zeng, D.-H., Yu, Z.-Y., Ai, G.-Y., Yang, D., & Mao, R. (2009). Effects of nitrogen addition on grassland species diversity and productivity in Keerqin Sandy Land. *Chinese Journal of Applied Ecology*, *20*(8), 1838–1844. Retrieved from Scopus.

Li, W., Wen, S., Hu, W., & Du, G. (2011). Root-shoot competition interactions cause diversity loss after fertilization: a field experiment in an alpine meadow on the Tibetan Plateau. *Journal of Plant Ecology*, *4*(3), 138–146. https://doi.org/10.1093/jpe/rtq031

Liess, A., & Kahlert, M. (2007). Gastropod grazers and nutrients, but not light, interact in determining periphytic algal diversity. *Oecologia*, *152*(1), 101–111. https://doi.org/10.1007/s00442-006-0636-4

Liess, Antonia, Lange, K., Schulz, F., Piggott, J. J., Matthaei, C. D., & Townsend, C. R. (2009). Light, nutrients and grazing interact to determine diatom species richness via changes to productivity, nutrient state and grazer activity. *Journal of Ecology*, *97*(2), 326–336. https://doi.org/10.1111/j.1365-2745.2008.01463.x

Liira, J., Ingerpuu, N., Kalamees, R., Moora, M., Paertel, M., Puessa, K., … Zobel, M. (2012). Grassland diversity under changing productivity and the underlying mechanisms - results of a 10-yr experiment. *Journal of Vegetation Science*, *23*(5), 919–930. https://doi.org/10.1111/j.1654-1103.2012.01409.x

Longhi, M. L., & Beisner, B. E. (2010). Patterns in taxonomic and functional diversity of lake phytoplankton. *Freshwater Biology*, *55*(6), 1349–1366. https://doi.org/10.1111/j.1365-2427.2009.02359.x

MacDougall, A. S., Bennett, J. R., Firn, J., Seabloom, E. W., Borer, E. T., Lind, E. M., … Stevens, C. J. (2014). Anthropogenic-based regional-scale factors most consistently explain plot-level exotic diversity in grasslands. *Global Ecology and Biogeography*, *23*(7), 802–810. https://doi.org/10.1111/geb.12157

Mattingly, W. B., Swedo, B. L., & Reynolds, H. L. (2010). Interactive effects of resource enrichment and resident diversity on invasion of native grassland by Lolium arundinaceum. *Plant Ecology*, *207*(2), 203–212. https://doi.org/10.1007/s11258-009-9665-5

McEachern, P., Prepas, E. E., & Planas, D. (2002). Phytoplankton in boreal SubArctic lakes following enhanced phosphorus loading from forest fire: Impacts on species richness, nitrogen and light limitation. *Lake and Reservoir Management*, *18*(2), 138–148.

Mette, E. M., Vanni, M. J., Newell, J. M., & Gonzalez, M. J. (2011). Phytoplankton communities and stoichiometry are interactively affected by light, nutrients, and fish. *Limnology and Oceanography*, *56*(6), 1959–1975. https://doi.org/10.4319/lo.2011.56.6.1959

Murphy, K. J., Dickinson, G., Thomaz, S. M., Bini, L. M., Dick, K., Greaves, K., … Wingfield, R. A. (2003). Aquatic plant communities and predictors of diversity in a sub-tropical river floodplain: The upper Rio Paraná, Brazil. *Aquatic Botany*, *77*(4), 257–276. https://doi.org/10.1016/S0304-3770(03)00108-6

Ostertag, R., Giardina, C. P., & Cordell, S. (2008). Understory colonization of Eucalyptus plantations in Hawaii in relation to light and nutrient levels. *Restoration Ecology*, *16*(3), 475–485. https://doi.org/10.1111/j.1526-100X.2007.00321.x

Patrick, L. B., Fraser, L. H., & Kershner, M. W. (2008). Large-scale manipulation of plant litter and fertilizer in a managed successional temperate grassland. *Plant Ecology*, *197*(2), 183–195. https://doi.org/10.1007/s11258-007-9369-7

Petersen, U., & Isselstein, J. (2015). Nitrogen addition and harvest frequency rather than initial plant species composition determine vertical structure and light interception in grasslands. *Aob Plants*, *7*, plv089. https://doi.org/10.1093/aobpla/plv089

Rajaniemi, T. K. (2002). Why does fertilization reduce plant species diversity? Testing three competition-based hypotheses. *Journal of Ecology*, *90*(2), 316–324. https://doi.org/10.1046/j.1365-2745.2001.00662.x

Ren, F., Song, W., Chen, L., Mi, Z., Zhang, Z., Zhu, W., … He, J.-S. (2017). Phosphorus does not alleviate the negative effect of nitrogen enrichment on legume performance in an alpine grassland. *Journal of Plant Ecology*, *10*(5), 822–830. https://doi.org/10.1093/jpe/rtw089

Ren, Z., Li, Q., Chu, C., Zhao, L., Zhang, J., Dexiecuo Ai, … Wang, G. (2010). Effects of resource additions on species richness and ANPP in an alpine meadow community. *Journal of Plant Ecology*, *3*(1), 25–31. https://doi.org/10.1093/jpe/rtp034

Roscher, C., Schmid, B., Kolle, O., & Schulze, E.-D. (2016). Complementarity among four highly productive grassland species depends on resource availability. *Oecologia*, *181*(2), 571–582. https://doi.org/10.1007/s00442-016-3587-4

Siebenkaes, A., Schumacher, J., & Roscher, C. (2016). Resource Availability Alters Biodiversity Effects in Experimental Grass-Forb Mixtures. *Plos One*, *11*(6), e0158110. https://doi.org/10.1371/journal.pone.0158110

Siebenkäs, A., & Roscher, C. (2016). Functional composition rather than species richness determines root characteristics of experimental grasslands grown at different light and nutrient availability. *Plant and Soil*, *404*(1), 399–412. https://doi.org/10.1007/s11104-016-2853-x

Siebenkäs, A., Schumacher, J., & Roscher, C. (2017). Trait variation in response to resource availability and plant diversity modulates functional dissimilarity among species in experimental grasslands. *Journal of Plant Ecology*, *10*(6), 981–993. https://doi.org/10.1093/jpe/rtw110

Singh, G., & Shukla, S. (2011). Effects of Azadirachta indica Canopy Manipulation and Nitrogen Fertilization on Diversity and Productivity of Herbaceous Vegetation in an Arid Environment of India. *Arid Land Research and Management*, *25*(2), 128–149. https://doi.org/10.1080/15324982.2011.554955

Spehn, E. M., Hector, A., Joshi, J., Scherer-Lorenzen, M., Schmid, B., Bazeley-White, E., … Lawton, J. H. (2005). Ecosystem effects of biodiversity manipulations in European grasslands. *Ecological Monographs*, *75*(1), 37–63. https://doi.org/10.1890/03-4101

Stevens, M. H. H., & Carson, W. P. (2001). Phenological complementarity, species diversity, and ecosystem function. *Oikos*, *92*(2), 291–296. https://doi.org/10.1034/j.1600-0706.2001.920211.x

Stevens, M. H. H., Shirk, R., & Steiner, C. E. (2006). Water and fertilizer have opposite effects on plant species richness in a mesic early successional habitat. *Plant Ecology*, *183*(1), 27–34. https://doi.org/10.1007/s11258-005-9003-5

Sun, X., Yu, K., Shugart, H. H., & Wang, G. (2016). Species richness loss after nutrient addition as affected by N:C ratios and phytohormone GA(3) contents in an alpine meadow community. *Journal of Plant Ecology*, *9*(2), 201–211. https://doi.org/10.1093/jpe/rtv037

Tanentzap, A. J., & Bazely, D. R. (2009). Propagule pressure and resource availability determine plant community invasibility in a temperate forest understorey. *O-ikos*, *118*(2), 300–308. https://doi.org/10.1111/j.1600-0706.2008.17069.x

Tang, L., Cheng, C., Wan, K., Li, R., Wang, D., Tao, Y., … Chen, F. (2014). Impact of Fertilizing Pattern on the Biodiversity of a Weed Community and Wheat Growth. *Plos One*, *9*(1), e84370. https://doi.org/10.1371/journal.pone.0084370

Tang, L., Wan, K., Cheng, C., Li, R., Wang, D., Pan, J., … Chen, F. (2014). Effect of fertilization patterns on the assemblage of weed communities in an upland winter wheat field. *Journal of Plant Ecology*, *7*(1), 39–50. https://doi.org/10.1093/jpe/rtt018

Tilman, D. (1987). Secondary Succession and the Pattern of Plant Dominance Along Experimental Nitrogen Gradients. *Ecological Monographs*, *57*(3), 190–214. https://doi.org/10.2307/2937080

Tilman, D. (1993). Species Richness of Experimental Productivity Gradients: How Important is Colonization Limitation? *Ecology*, *74*(8), 2179–2191. https://doi.org/10.2307/1939572

Tilman, D., Wedin, D., & Knops, J. (1996). Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature*, *379*(6567), 718–720. https://doi.org/10.1038/379718a0

Unrein, F., & Vinocur, A. (1999). Phytoplankton structure and dynamics in a turbid Antarctic Lake (Potter Peninsula, King George Island). *Polar Biology*, *22*(2), 93–101. https://doi.org/10.1007/s003000050395

Wacker, L., Baudois, O., Eichenberger-Glinz, S., & Schmid, B. (2009). Effects of plant species richness on stand structure and productivity. *Journal of Plant Ecology*, *2*(2), 95–106. https://doi.org/10.1093/jpe/rtp010

Ward, D., Kirkman, K., & Tsvuura, Z. (2017). An African grassland responds similarly to long-term fertilization to the Park Grass experiment. *PLoS ONE*, *12*(5). https://doi.org/10.1371/journal.pone.0177208

Weilhoefer, C. L., Jakstis, K., & Fischer, C. (2017). Response of Primary Producer Communities to Short-Term Nutrient Additions in a Pacific Northwest Estuarine Tidal Wetland. *Wetlands*, *37*(4), 687–696. https://doi.org/10.1007/s13157-017-0899-z

Wilson, S. D., & Tilman, D. (1991). Components of plant competition along an experimental gradient of nitrogen availability. *Ecology*, *72*(3), 1050–1065. Retrieved from Scopus.

Xenopoulos, M. A., & Frost, P. C. (2003). UV radiation, phosphorus, and their combined effects on the taxonomic composition of phytoplankton in a boreal lake. *Journal of Phycology*, *39*(2), 291–302.

Appendix 3: Tables

Table S5.1: List of 74 papers included in the qualitative analysis. The hypothesis ID follows the notation in Fig S5.1. (n.s: not specified)

Citation	Ecosystem	Number of Independent Studies	Hypothesis ID
(Tilman, 1987)	grassland	4	**1a**
(Wilson & Tilman, 1991)	grassland	1	**1e**
(Tilman, 1993)	grassland	4 (4 fields)	**1a**
(Huber, 1994)	grassland	1	**2c**
(Chapin et al. 1995)	tundra	2 (2 years)	**2b**
(Tilman et al. 1996)	grassland	2 (1 field, 1 lab experiments)	**5**
(Kleijn & Van Der Voort, 1997)	grassland	1	**1a**
(Grace & Pugesek, 1997)	wetland	1	**14**
(Foster & Gross, 1998)	grassland	1	**1c**
(Unrein & Vinocur, 1999)	aquatic	1	**n.s.**
(Eek & Zobel, 1997)	grassland	1	**2f**
(Stevens & Carson, 2001)	grassland	1	**3b**
(Gough et al. 2002)	tundra	1	**2a**
(McEachern et al. 2002)	aquatic	10 (10 locations)	**n.s.**
(Rajaniemi, 2002)	grassland	1	**2a**
(Murphy et al., 2003)	aquatic	4 (4 different habitat types)	**n.s.**
(Fridley, 2003)	grassland	1	**3a**
(Baer et al. 2003)	grassland	1	**1e**
(Chiarucci et al. 2004)	grassland	1	**1a**
(Bymers et al. 2005)	aquatic	1	**n.s.**
(Spehn et al., 2005)	grassland	8 (8 sites in different locations)	**5**
(Gross et al., 2005)	grassland	1	**1d**
(Klanderud & Totland, 2005)	grassland	1	**1j**
(Eriksson et al. , 2006)	aquatic	1	**2e**
(Stevens et al. 2006)	grassland	1	**1n**
(Barnett & Beisner, 2007)	aquatic	1	**n.s.**
(Liess & Kahlert, 2007)	aquatic	1	**2c**
(Gendron & Wilson, 2007)	grassland	1	**1k**
(Lamb, 2008)	grassland	1	**13**
(Patrick et al. 2008)	grassland	1	**1c**
(Crossetti et al. 2008)	aquatic	3 (3 independent phases of data collection)	**n.s.**
(Ostertag et al. 2008)	forest	1	**2a**
(Hautier et al. 2009)	grassland	1	**2a**
(Li et al., 2009)	grassland	1	**1a**
(Wacker et al. 2009)	grassland	1	**4**
(Liess et al., 2009)	aquatic	1	**2c**
(Tanentzap & Bazely, 2009)	grassland	1	**2d**

(Cardinale et al., 2009)	aquatic	1	**12**
(Becker et al., 2010)	aquatic	10 (10 independent combinations of nutrients)	**n.s.**
(Ren et al., 2010)	grassland	1	**1f**
(Mattingly et al. 2010)	grassland	1	**3a**
(Longhi & Beisner, 2010)	aquatic	1	**n.s.**
(Clark & Tilman, 2010)	grassland	1	**1b**
(Singh & Shukla, 2011)	grassland	1	**2a**
(Dickson & Foster, 2011)	grassland	1	**6**
(Mette et al. 2011)	aquatic	1	**2c**
(Li et al. 2011)	grassland	1	**2a**
(Liira et al., 2012)	grassland	4 (4 functional groups or mixture)	**1a**
(Jarchow & Liebman, 2012)	grassland	1	**4**
(Gazol et al., 2013)	grassland	1	**10**
(Xenopoulos & Frost, 2003)	aquatic	4 (this is NutNet data, split into 4 regions and means are taken in those separately)	**2a**
(MacDougall et al., 2014)	grassland	4 (4 independent combinations of nutrients)	**n.s.**
(Tang et al., 2014)	grassland	2 (nonclonal and mixture experiments)	**1a**
(Dickson et al. 2014)	grassland	1 (these 40 NutNet sites are considered as replicates)	**1a**
(Borer et al., 2014)	grassland	1	**1i**
(Tang et al., 2014)	grassland	1	**1a**
(Gooden & French, 2015)	wetland	1	**1g**
(Petersen & Isselstein, 2015)	grassland	1	**1h**
(Harpole & et. al., 2016)	grassland	1 (these 45 NutNet sites are considered as replicates)	**9**
(Roscher, et al. 2016)	grassland	1	**3a**
(Siebenkäs & Roscher, 2016)	grassland	1	**3a**
(Han & Cui, 2016)	aquatic	1	**n.s.**
(Fessel et al. 2016)	grassland	1	**7**
(Siebenkaes et al. 2016)	grassland	1	**3a**
(Sun et al. 2016)	grassland	1	**1a**
(Grace et al., 2016)	grassland	1	**8**
(Harpole et al., 2017)	grassland	same as Harpole et al. 2016	**9**
(Ward et al. 2017)	grassland	1	**1m**
(DeMalach et al., 2016)	grassland	2 (hill and valley)	**15**
(DeMalach et al., 2017)	grassland	same as Harpole et al. 2016	**11**
(Weilhoefer et al. 2017)	wetland	1	**1a**
(Gross & Mittelbach, 2017)	grassland	2 (clonal and mixed treatments)	**1a**
(Ren et al., 2017)	grassland	1	**1a**
(Siebenkäs et al. 2017)	grassland	1	**3a**
		123 independent studies	

Table S5.2: Additional variables considered relevant for this system in the literature

Type of variable	Variable	N° Studies	Hypothesis ID
Other treatments	Grazing	2	1i, 2c
	Seed addition	3	1b, 1d, 2d
	Disturbance of the soil	2	3b, 14
	Cover reduction	5	1d, 1h, 1k, 2f
	Litter presence/removal	7	1b, 1c, 1h, 1k, 9, 11, 13
Environmental	Soil depth	1	1l
	pH	1	1m
	Habitat complexity	1	2e
	Habitat type	1	15
	Salinity	1	14
	Flooding	1	14
	Temperature	3	1j, 2b, 7
Availability of nutrients	Irrigation/Water availability	1	1n
	Spatial Heterogeneity (nutrients)	2	1d, 10
	Number of added resources (nutrients)	3	1f, 9, 11
Competition	Presence of neighboring plants	1	1e
	Invasion (competition with invasive species)	1	1g
	Competitive effect (function of biomass)	1	15
	Plant cover	1	7

Table S5.3: Tally of interactions of hypothesis number 12 (Cardinale *et al.* 2009 – highlighted cells) reported in all other papers. RD: Raw Data required

AU	**Type of coefficient reported**	**Number of independent observations**	Diversity -> Biomass	Light -> Diversity	Nutrients -> Diversity	Nutrients -> Biomass	Light -> Biomass
(Tilman, 1987)	Means (no errors shown)	4			RD	RD	
(Wilson & Tilman, 1991)	Regression coefficients	1			RD	1	
(Tilman, 1993)	Means and errors, regression coefficients	4			4	4	
(Huber, 1994)	Means and errors	1		RD	RD	1	1
(Chapin *et al.*, 1995)	Means and errors	2		2	2	2	2
(Tilman et al. 1996)	Means and errors	2	2				
(Kleijn & Van Der Voort, 1997)	Regression coefficients	1			1	1	
(Grace & Pugesek, 1997)	SEM coefficients	1		1	1	1	
(Foster & Gross, 1998)	Means and errors	1			1	1	
(Unrein & Vinocur, 1999)	Non causal correlation coeffs	1		RD	RD	RD	RD
(Eek & Zobel, 1997)	None	1		RD	RD	RD	RD
(Stevens & Carson, 2001)	None	1	RD			RD	RD
(Gough et al. 2002)	Means and errors	1		1	1	1	1

(McEachern et al. 2002)	Non causal, Means and errors	10		RD	RD	RD	RD
(Rajaniemi, 2002)	Means and errors	1		1	1	1	1
(Murphy et al., 2003)	Means and errors	4		4	4	4	4
(Fridley, 2003)	Means and error	1	1			1	1
(Baer et al. 2003)	Means and errors	1			1	1	
(Chiarucci et al. 2004)	Data points	1			RD	RD	
(Bymers et al. , 2005)	Non causal correlations	1		RD	RD	RD	RD
(Spehn et al., 2005)	Means and errors	8	8				
(Gross et al., 2005)	Means and errors	1			1	1	
(Klanderud & Tot-land, 2005)	Means and errors, re-gression coefficients	1			1	1	
(Eriksson, et al. 2006)	Means and errors	1		1	1	1	1
(Stevens et al. 2006)	Means and errors	1			1	1	
(Barnett & Beisner, 2007)	Non causal correlations	1		RD	RD	RD	RD
(Liess & Kahlert, 2007)	Means and errors	1		1	1	1	1
(Gendron & Wil-son, 2007)	Means and errors	1			1	1	
(Lamb, 2008)	SEM coefficients	1		1	1	1	1
(DeMalach et al., 2016)	Raw data in supplemen-tary material	2			RD	RD	

(Crossetti et al. 2008)	Non causal correlations	3		RD	RD		
(Ostertag, et al. 2008)	Means and errors, correlation coefficients	1		1	1	1	1
(Hautier et al. 2009)	Means and errors	1		1	1	1	1
(Li et al., 2009)	Means and errors	1			1	1	
(Wacker et al. 2009)	None	1	RD			RD	
(Tanentzap & Bazely, 2009)	Means and errors	1		1	1	RD	RD
(Cardinale et al., 2009)	SEM coefficients	1	1	RD	RD	RD	RD
(Becker et al., 2010)	Non causal correlations	1		RD	RD	RD	RD
(Ren et al., 2010)	Means and errors	10			10	10	
(Patrick et al. 2008)	Means and errors	1			1	1	
(Longhi & Beisner, 2010)	Non causal correlations	1		RD	RD	RD	RD
(Clark & Tilman, 2010)	Means and errors	1			1	1	
(Singh & Shukla, 2011)	Means and errors	1		1	1	1	1
(Dickson & Foster, 2011)	Means and errors	1		1	1	1	1
(Mette et al. 2011)	Means and errors	1		1	1	1	1
(Li et al. 2011)	Means and errors	1		1	1	1	1
(Liira et al., 2012)	Means and errors	1			1	1	

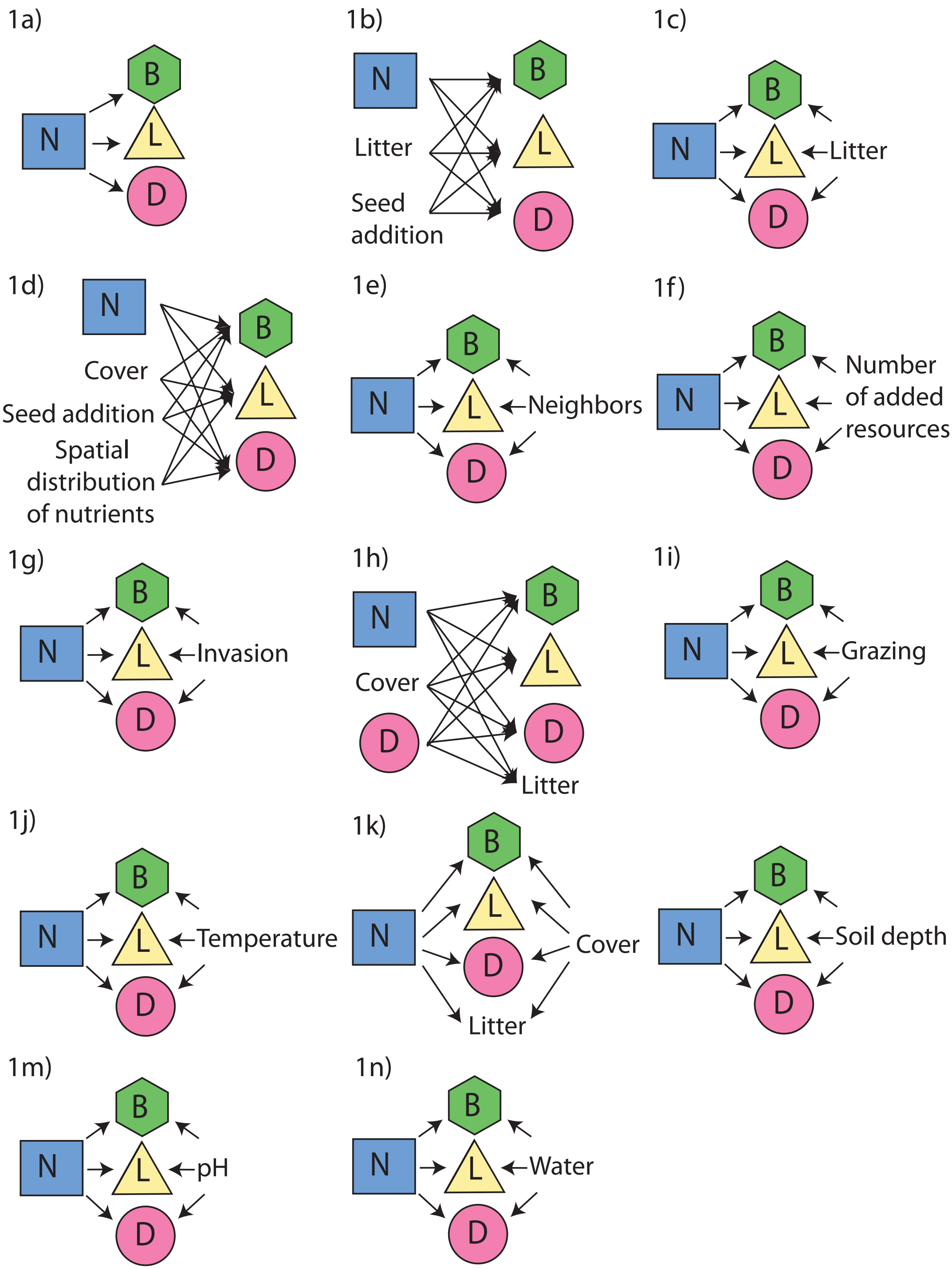
(Jarchow & Lieb-man, 2012)	Means and errors	4	4			4	
(Gazol et al., 2013)	Means and errors, re-gression coefficients	1		1	1	1	
(Xenopoulos & Frost, 2003)	None	1		RD	RD	RD	RD
(MacDougall et al., 2014)	Non causal correlations	4		RD	RD		
(Tang et al., 2014)	Means and errors	4			4	4	
(Dickson et al. 2014)	Means and errors	2			2	2	
(Borer et al., 2014)	Means and errors	1			1	1	
(Tang et al., 2014)	None	1			RD	RD	
(Gooden & French, 2015)	Means and errors	1			RD	1	
(Mattingly, Swedo, & Reynolds, 2010)	Means and errors	1	1			1	1
(Petersen & Is-selstein, 2015)	Means and errors	1	1		1	1	
(S. Harpole & et. al., 2016)	Means and errors	1					
(Roscher, et al. 2016)	Means and errors	1	1			RD	RD
(Siebenkäs & Roscher, 2016)	Only significances shown	1	RD			RD	RD
(Han & Cui, 2016)	Non causal correlations	1		RD	RD	RD	RD
(Fessel et al. 2016)	SEM coefficients	1			1		1

(Siebenkaes et al. 2016)	Means and errors	1	1			1	1
(Sun et al. 2016)	Means and errors	1			1	1	
(Grace et al., 2016)	SEM regression coeffi-cients	1		1		1	
(Ward et al. 2017)	Means and errors	1			1	1	
(DeMalach et al., 2017)	Standarized coefficients	1		1			
(Liess et al., 2009)	Means and errors	1		1	1	1	1
(Harpole et al., 2017)	idem Harpole et al. 2016						
(Weilhoefer et al. 2017)	Means and errors	1			1	1	
(Gross & Mittel-bach, 2017)	Means and errors	2			2	2	
(Ren et al., 2017)	Means and errors	1			1	1	
(Siebenkäs et al. 2017)	None	1	RD			RD	RD
		Total effect sizes + RD	**24**	**36**	**82**	**89**	**38**
		Total effect sizes	**20**	**23**	**61**	**70**	**23**

<u>Appendix 4: Figures</u>

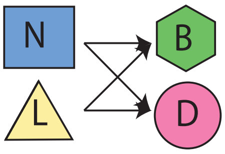
Fig S5.1: List of 34 hypotheses identified from the literature, grouped by compatibility of causality between variables of interest.

1) Compatible hypotheses with nutrients as effect variable

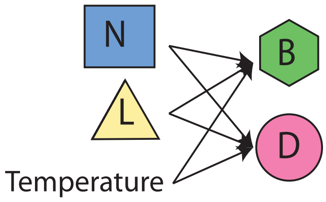


2) Compatible hypotheses with nutrient and light as effect variables

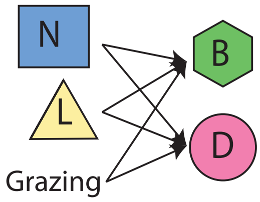
2a)



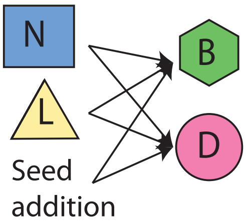
2b)



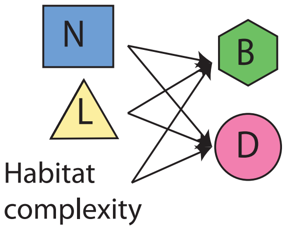
2c)



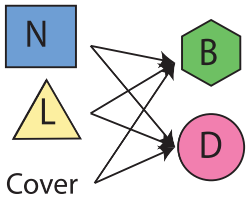
2d)



2e)

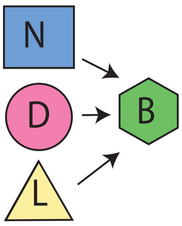


2f)

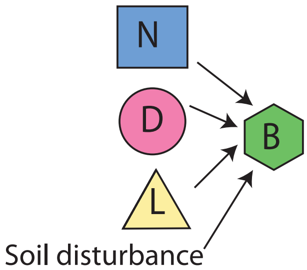


3) Compatible hypotheses with nutrient, diversity and light as effect variables

3a)

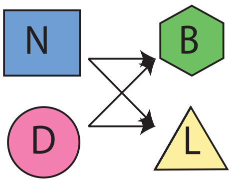


3b)

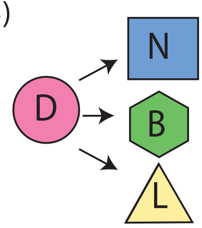


Proposed hypotheses without compatible systems

4)



5)



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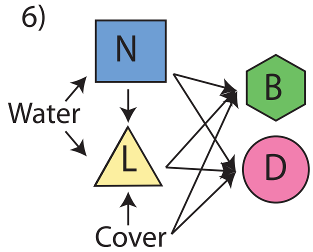
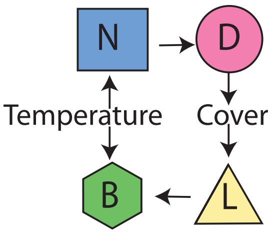


7)



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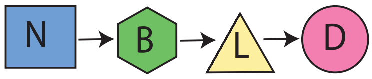
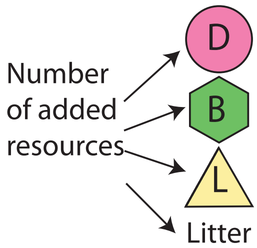
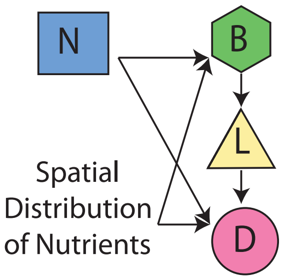


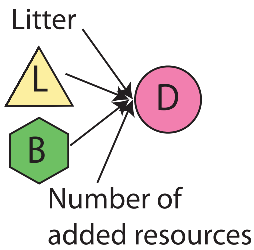
9)



10)



11)



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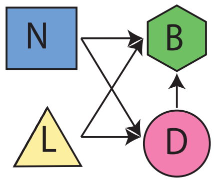
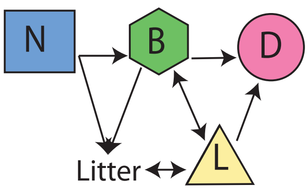
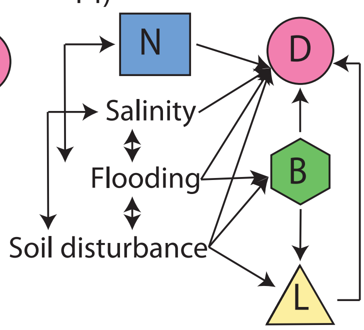


13)



14)



15)

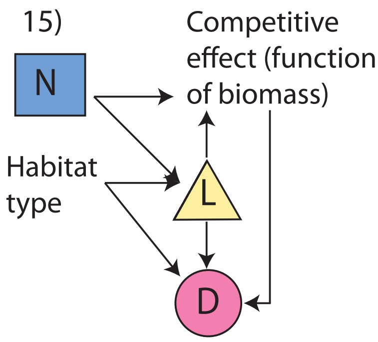
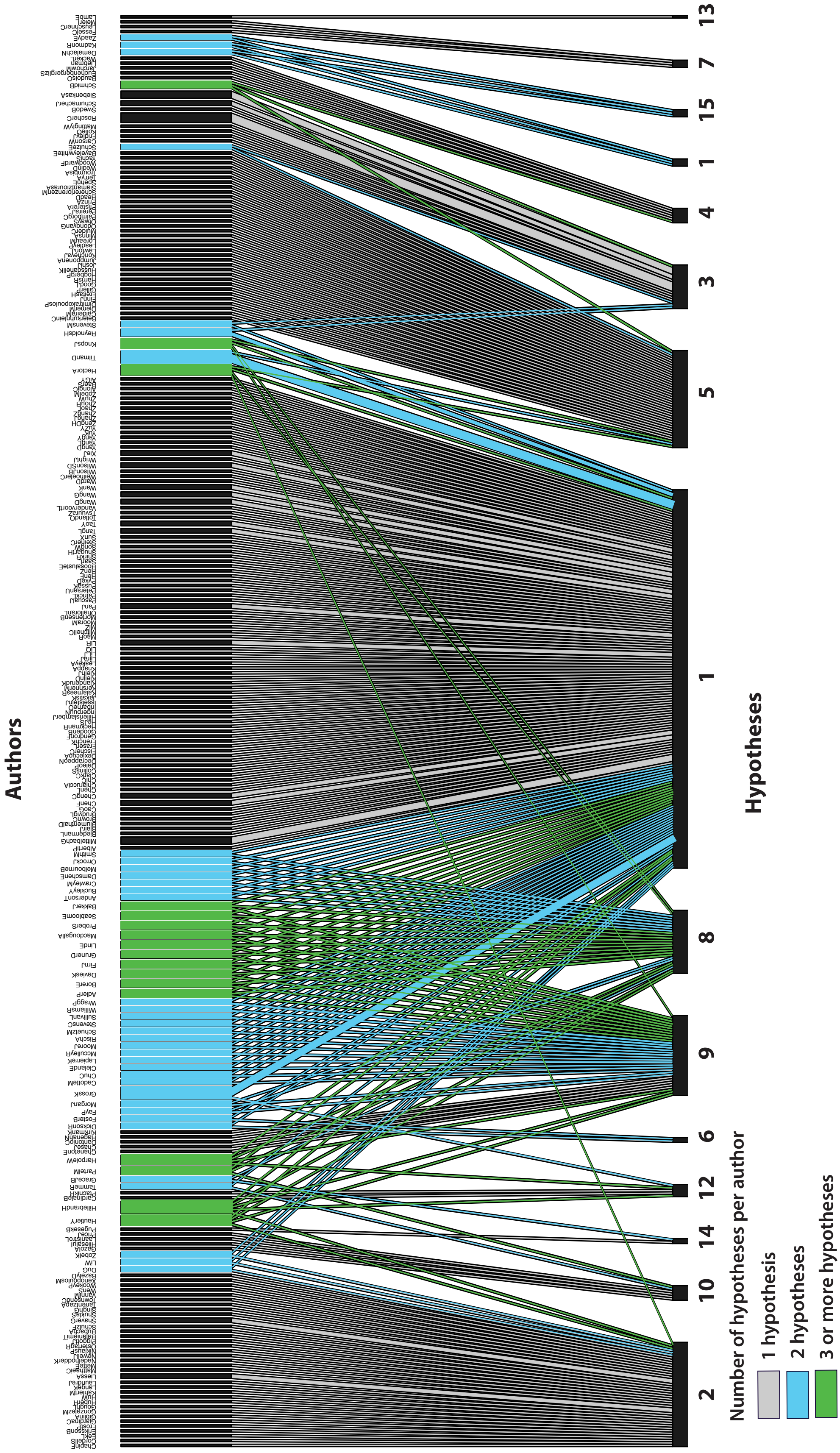


Fig. S5.2: Full Social Network Analysis plot. Authors with 1, 2 and 3 hypotheses are color-coded differently for better visualization.



6. General Discussion

6.1 Overview

In this thesis, I explored ways of integrating data and perspectives in global change sciences. Studying diversity as an emergent property of a group of elements, can advance knowledge on how systems work holistically. Some of the main elements to research in socio-ecological systems under global change are people's understandings, data and hypotheses.

Research synthesis across disciplines is required to advance knowledge on how socio-ecological systems work, yet their complexity and the heterogeneity in data available make this task challenging. There are also different levels of integration (local to global) and feedbacks between variables that need to be taken into account. Furthermore, knowledge in science does not advance necessarily in a directional way; multiple hypotheses, sometimes complementary and other times contradictory, are continuously being proposed and tested. Communication, collaboration and synthesis efforts are required to organize this diversity of information.

Land use changes, among them nutrient inputs through fertilization, are some of the global-change drivers that are the most detrimental to biodiversity and the long term sustainability of ecosystem services (Kennedy et al., 2019). Yet we continue to change the land in order to increase land productivity, supposedly with the goal of increasing well-being, in particular to improve people's nutritional status and alleviate poverty. However, we do not always reach our goals; some interventions are more successful than others and effects on biodiversity, people and productivity may be context-dependent. The interactions between all components of this system have never been studied together at large scale, even though results from such analysis would be useful for ecosystem management. Furthermore, there may be a close connection between the way we treat the land, the level of biodiversity that we support and our understanding of how ecosystems work, or even more specifically about what biodiversity is. Ultimately, these are plausible connections that I aimed to examine using quantitative and qualitative approaches.

6.2 Outcomes

A summary of the main outcomes of the thesis can be found in table 6.1. In the first chapter of the thesis, I developed a conceptual framework that stands on previous learning theories, on how people's understandings of biodiversity may develop, in relation with their understanding of diversity. Using this approach, everyday experiences such as playing, cooking, transport, housing, interpersonal relations would all contribute to people's views on biodiversity. This kind of approach has not been taken into account in the biodiversity literature up to now, a research gap that became evident through the review of literature. Most research up to now in biodiversity education has focused on translating data and research to untrained audiences, but few have focused on the sources of influence that may be contributing to education, particularly in early experiences (Brewer, 2006).Through the applied examples (children games and food-related activities) that I viewed under the light of this conceptual framework, new sources of misconceptions could be identified: in the case of children games, the language and lack of variability used in classification puzzles; in the case of food-related activities, the lack of capacity to track biodiversity in our diets. Moreover, this chapter was done in collaboration with many authors from diverse disciplines such as ecology, ethics and human geography, so it is an integration of current perspectives of this group on the matter.

In the second chapter, I used a network of variables from a socio-ecological complex system inspired in the conceptual frameworks developed for large-scale science-policy programs, such as the Millennium Ecosystem Assessment. Through literature research, I selected and defined land-use change, productivity, biodiversity, and nutritional status as variables of interest and performed a review for each pairwise interaction, in the absence of studies reporting the four of them. For each interaction, I could suggest new working hypotheses, research gaps, and general patterns of effects. Results show detrimental aspects of land-use change or intensification, not only on biodiversity, as well documented in the literature, but also in productivity in the long term. These result support a large body of literature on land-use impacts, but also add a level of importance to establishing links with other aspects of the interaction among ecosystems and people. Although fewer studies were found that could be used for analyzing the relation with human nutritional status, the ones used showed a positive impact of increasing biodiversity and productivity, at least at local scales. When described qualitatively using more studies, their results were not conclusive and this was mainly due to reporting issues and lack of standardized experimental designs, which are complicated for social studies (Berti et al., 2004).

In the third chapter, I analyzed a narrower system of interactions, between only one type of land-use change (nutrient addition/fertilization), biodiversity, productivity, and competition for resources in plants. A timeless debate puts emphasis on disentangling the strength of the mechanisms determining biodiversity and productivity in plant communities (Fay et al., 2015; Harpole et al., 2016). The main outcome of my review was a summary of all hypotheses tested in the literature for this system, on the top of which are the five most tested ones (each with less than ten tests in the literature, except for the least complex one – nutrient addition – which had around 30 tests). To arrive at this list, I looked into the statistics of each paper, by developing a method that could be thought of as backward inference. I suggest that this method could be useful in other research areas where there is a current need for synthesizing hypotheses, such as ecosystem multifunctionality. This method differs from previous ones used in the literature in that usually reviews are based on the intended hypotheses from original studies, not the ones actually tested through statistics. The results from this chapter support ongoing research that aims at reproducibility and neglected ecosystems (Costanza et al., 2007; Flombaum & Sala, 2008; Roscher et al., 2013). Results suggest that alternative, more ambitious experiments that aim to better represent the complexity of natural systems (e.g., by including more factors and manipulations), coupled with more advanced statistical techniques, such as network analyses and structural equation modeling, could be of aid in determining the mechanisms underlying observed outcomes (Cheung, 2015; Grace et al., 2014; Grace & Pugesek, 1997).

Table 6.1: Summary of main specific chapter outcomes

	Question addressed	Outcomes
Chapter 1: Improving our understanding of biodiversity through everyday experiences	How does the concept of biodiversity can develop in people's minds?	A review of the literature showed relevant studies on how biodiversity can be taught at school but few on how other activities or types of explorations shape this understanding.
		I developed a conceptual framework with foundation in constructivist learning theory where understanding of biodiversity starts its development before formal education in natural sciences, during early explorations. In this period of learning misconceptions could be formed.
	What are the factors that affect our understanding of the concept of biodiversity?	Early explorations and general everyday activities, even when outside formal education, could affect our understanding of what biodiversity is and its relevance for ecosystem functioning. Other possible influences are for example, cultural aspects, family and social bonds and economic status.
	What do researchers and lecturers from both social and natural sciences think about how people's understanding of biodiversity develops?	I integrated the perspectives of 16 researchers from ecology, geography, human geography, ethics and education. They all agree in that further practical research into the influence of everyday experiences on the way we understand biodiversity is needed and timely. This research would need a transdisciplinary approach, working closely with, for example, children game developers, practitioners and farmers.

	Question addressed	Outcomes
Chapter 2: Systemic analysis of interactions between land-use change, biodiversity, productivity, and nutrition	What is the strength of the interactions between multiple components of the global change system between land use change, biodiversity, productivity and nutritional status?	A meta-analysis between the components of this system showed a large negative effect of land use on biodiversity, a moderate negative effect on productivity and a large positive effect on nutritional status of the population (provided that biodiversity and productivity increased with the land use). A meta-analysis between biodiversity and productivity showed a large positive effect of biodiversity on productivity, for plant communities where mixtures were manipulated.
	Can this strength be quantified using published studies from diverse sources?	The strength of some but not all interactions (the ones described above) could be quantified with a meta-analysis using information in published studies. This approach was not useful with effects that have not been repeatedly tested in similar experimental designs, be it because of heterogeneity of approaches or due to research gaps. Where descriptive reviews were used, conclusions were mixed, in both direction and strength.
	What are the advantages and challenges of performing systemic analyses with multiple components and inter-disciplinary?	An interdisciplinary approach allowed us to analyze systems holistically, potentially in similar ways to how systems work in nature. In the system used in this chapters, studies from ecology, geography and econometrics were integrated in one network of variables. Usually hidden patterns, such as the effects of land use management decisions by owners on biodiversity levels through productivity could be explored with this system.
		The main challenge to integration was the large heterogeneity between hypotheses, experimental designs and ways of reporting. Added to the natural complexity of the multifaceted components of global change, this reduces the number of individual studies that can be used in comparative studies or synthesis. The recommendation to overcome this challenge would be not to suppress this heterogeneity but for the scientific community to agree in standard reporting practices and measurements that must always be published together with their preferred way. Maybe carrying more *question specific conferences*, instead of *discipline specific conferences*, would provide spaces for these discussions to develop.

	Question addressed	Outcomes
Chapter 3: Identification, comparison, and analysis of hypotheses in systematic review	What are the most tested hypotheses on competition for nutrition and light related to biodiversity and productivity in plant communities?	By looking at the statistical analyses of published papers, we derived 34 groups of compatible hypotheses that had been proposed and tested using at least the four main variables of interest in this study: light, nutrients, biodiversity and productivity. From this, only five had been tested more than once in the literature (ranging from 2 to 38 times)
	What is the difference between them?	The hypotheses tested differed in the level of complexity, which in turn translated to different experimental designs and statistics used in their analysis. The simplest hypotheses used one variable as effect and measured responses in all others, assuming direct (most of the time linear) effects. For example, the most tested one which is the use of nitrogen addition in plant plots and the measurement of biomass amount, light penetration and biodiversity changes in time. increasing level of complexity was shown by analyzing indirect effects aswell. Experimentally, the maximum amount of manipulated variables was 3 (light, using mirrors, biodiversity, modifying number of species present in mixtures and productivity by pruning the plants). More complex hypotheses used path coefficient analyses, over datasets where values for all components were taken with individual simple experimental designs.
	Is it possible to find out which of the internal mechanisms of determination of the plant community structure is stronger?	With the available published data it was not possible to determine the strength of the underlying mechanisms in this system. The recommendation is for each of the hypotheses to be tested repeatedly with standard designs as replicates or for existing trustworthy big datasets to be tested under several of the hypotheses simultaneously to find the better fit.

Overall, within this thesis I achieved a deeper level of understanding of the heterogeneity between studies in biodiversity and global change sciences, particularly for land-use change and biodiversity studies, and hope to have advanced research by providing some fundamental seeds for future studies in research synthesis.

6.3 Challenges

The main challenge for data integration was to find suitable data reported according to requirements for meta-analysis. A great part of studies found could not be used due to reporting issues such as lack of error reporting or problems with data sharing. Moreover, particularly within ecology and earth sciences, dealing with the heterogeneity of measures, experimental design and statistics is a challenge. For example, in the last chapter, it became evident that there is a lack of consensus in the scientific community. The lack of standard definitions, experimental designs, and measurements for key variables such as land-use intensity of management hindered the possibility of using more data and reaching more detailed conclusions besides general patterns. With regard to social aspects dealt with in this thesis, namely biodiversity understanding and nutritional status of populations following land use interventions, the recurrent challenge was to find quantitative data besides good theoretical conceptual maps and descriptive reports.

6.4 Next steps

Regarding biodiversity understanding, I hope to have inspired more experimental research and observational studies on how everyday activities affect our understanding (and miss-understandings) of biodiversity, across cultures. One example would be to test/observe whether traditional and alternative games for children actually alter their understanding of biodiversity. As for quantitative data synthesis, I would like to work further on redesigning the literature search protocol based on previous findings, so as to achieve a less heterogeneous database that can be used for more specific, local-scales questions. For the research community, the goal would be to encourage more research across disciplines and with multiple variables (e.g., with social, natural, and earth science aspects), even if it would be observational, so as to have a better idea on the dynamics of global-change systems. Furthermore, I would like to work further on the effects of performing meta-analysis with studies with diverse or similar hypotheses, to test the backwards inference method further. All chapters will be submitted for publication in peer-reviewed journals and data will be found in public online repositories.

7. Science outreach report

In the three chapters of my thesis, I worked on how integrate perspectives, data and hypotheses on how global change drivers interact with biodiversity. To perform this integration, I used literature from different disciplines from natural and social sciences, which was possible with further education in these disciplines and by establishing collaborations with other researchers. Part of this further training was in science communication, policy-making and education, through which I developed a deeper understanding of current societal challenges in urban ecology, agro-ecology and sustainable development, largely related to the way we use the land and we manage biodiversity – the main topics of my thesis. This connection with my thesis research prompt me to actively participate in a number of science outreach projects by the University of Zurich (Biodiversity Means Life, Science Lab UZH, Global Science Film Festival), to be member of the Sustainability Committee of the Faculty of Science, and was involved in variety of local and national programs (e.g., myClimate, St.Gallen Leaders of Tomorrow, Climathon, IUCN, WWF). Through these science outreach projects I found ways to give meaning to my research also outside academia. They also encouraged me to rethink my research from different angles and understand diverse perspectives. Engaging in science outreach was very rewarding and gave me a sense of connection with the community of Zurich. In this section of the thesis, I summarize the key experiences of the collaborations done in the framework of the University of Zurich.

7.1 Biodiversity Means Life (BML)

Supervisor: Dr. Morana Mihaljević

BML is a science outreach project of the University of Zurich that provides a platform for conversations between researchers and the general audience. Though the BML researchers have an opportunity to discuss their research with the general public. To do that more effectively BML offers training for doctoral students and researchers in science communication and assisting in the development of activities that translate academic research into informal science education. Within this project, I developed two activities that relate mostly to my chapters 1 and 2:

a) **Naturalness levels of the landscape:** In chapter 1, I addressed the topic of how people may perceive and understand biodiversity in different ways, according to their upbringings, education and everyday experiences. One way in which we interact we biodiversity directly is by being outdoors in nature. I asked myself: how do different people perceive the biodiversity in the landscape, by its level of human intervention (as being natural or artificial)?

   To bring attention to the topic of ecological naturalness, I wrote a story for general public in which I describe the different elements of landscapes and what is usually considered as different degrees of human intervention (Appendix O, 7.3.1a). To engage in discussions with visitors of the BML tent, I made a slide show of pictures showing landscapes with different degrees of human intervention (e.g., Figure 7.1). I would show the pictures to interested people from the audience and ask them series of questions, for example: Is this a natural landscape for you? How would you feel in this landscape? What landscape looks more pleasant to you? Which elements of this landscape denote humans have modify it? How much of the land you think should be left without intervention?

   I used the story and the slide-show as tools to help raise awareness of the level of modification of land use change and the elements of the landscape that we have come to naturalize, perhaps because they are aesthetically pleasant (e.g., straight shore rivers, introduced tree species such as palms, vineyards).

Fig. 7.1: Nature vs. artificial slideshow (example of images)

Outcome: This activity worked particularly well among young adults and adults, who took a moment to reflect on their views on nature and their relationship with it. Are the Swiss Alps natural? Is it "wrong" to modify nature for our well-being? How much of the land should be left untouched by humans and why? These are some of the recurrent topics during the interplay.

b) **Biodiversity in land use changes:** In chapter 2, I perform a literature and data integration on how modifying the land has an impact on reducing the number of species, and at the same time how this has an impact on productivity and human health. To raise awareness on this issue and empower people to contribute with solutions on species conservation, I developed a story for general audience on the type of insects that play different roles in agriculture and the importance of preserving them in their own urban or semi-urban landscapes (Appendix 7.3.1b). To interact with the audience, I have developed an insect hotel game (Figure 7.2). Insect hotels have been suggested to be effective tools for environmental education (Agarie et al., 2015; Griffiths & Voigt, 2014; Vacha & Petr, 2018). I have modified a traditional insect hotel to fit the habitat requirements of a diversity of insects, such as pollinators and insect predators: native solitary bees, hoverflies, green lacewings, ladybirds and beetles. The selection of species to use was based on personal experience and literature (Griffiths & Voigt, 2014). The audience would have to match insects with their respective habitat requirements using a series of clues. To complement the game, I provided information on the life cycle of insects and instruction on how to build your own insect hotel and a home garden with native plants (sometimes we would provide seed bombs to that end).

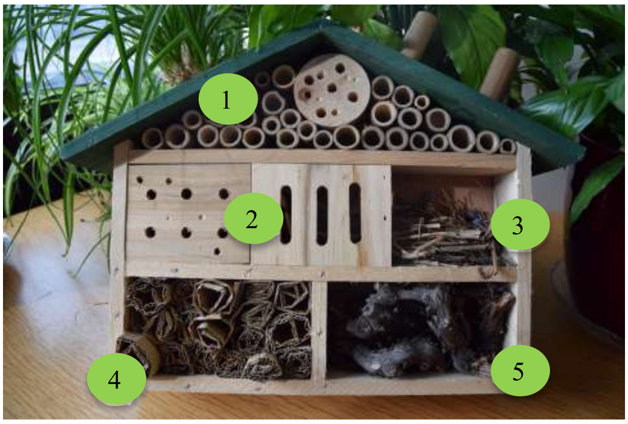


Fig. 7.2: Insect hotel game, for native bees, ladybugs, hoverflies, green lacewings and beetles. Clues: 1) native bees look nest in cylindrical tubes, 2) ladybirds overwinter in dark, quiet spaces, 3) hoverflies with rest in straws, 4) green lacewings are attracted to smooth, warm surfaces, 5) ground beetles rest on piles of wood or detritus. Sources: (Domoney, 2019; Gredler, 1999).

Outcome: This activity was particularly suitable for children and teens, who felt challenged by the game and learnt about diversity outside the typical pollinators (bees, butterflies). Following up questions would be related to how to build nests for native bees and other insects or how to fix existing ones that were not working (more often than not probably based on the humidity or sun exposure of where they were located).

7.2 Projects with the Sustainability Committee of the Faculty of Science (MNF)

Supervisors: Sara Petchey, Dr. Morana Mihaljević

The Sustainability Committee of the Faculty of Science provides financial help and mentoring for developing projects that enhance the sustainability of the Campus Irchel in one or more of three dimensions: social, economic and environmental. Within this program, I developed two activities, the Irchel Nature Trail and the Irchel Clean-up day.

Irchel Nature Trail

The Irchel Nature Trail is an educational trail with 20 knowledge stations about biodiversity though the UZH Campus Irchel (Figure 7.3). The trail was developed though collaboration of faculty staff members, students and postdocs (Figure 7.4). The aim of the trail is to make visible the nature in urban and semi-urban spaces and encourage communication between the university and the neighbours/park visitors. The 20 knowledge stations cover variety of topics from birds and bees to mountain ecology and biological interactions. The topics were chosen with aim of showcasing the biodiversity taxonomic groups and habitats at the campus and research focuses of the UZH scientists. The resulting topics were: 1 - Litter (Ecology), 2 - Birds (Species), 3 - Wetlands (Ecosystems), 4 - Microorganisms (Species), 5 - Bees (Species), 6 - Amphibians (Species), 7- Tree communication (Processes), 8 - Decomposition (Processes), 9 - Geology of the area (Geology), 10- History of the Campus (Institutional), 11- Dragon- and Damselflies (Species), 12- Forests (Ecosystems), 13- Rivers (Ecosystems), 14 - Mammals (Species), 15- Experimental Gardens (Research), 16 - Mountain Ecology (Ecology), 17- Inter-specific Interactions (Processes), 18 - Nature Games (Interactive), 19 - Butterflies (Species) and 20 - Green Cities (Ecology).

My contribution was as team coordinator, idea and content development, in particular for boards 1, 2, 3, 5, 6, 7, 8, 12, 15, 16, 18 and 20. Each knowledge station has a combination of features that provide a) core information scientific information, available in English and German, with supporting images, b) a map so the visitors can always know their location and location of other knowledge stations and c) a special feature which can be a key word, a quiz or an activity (Figure 7.5). Especially important is that each board is connected through a QR code to a website with more information about the topic, written by researchers from the university based on their research. Of special interest to me was designing schemes based on published research on wetlands, mountain ecology and urban ecology, for them to be self-explanatory but still complex enough that educators using the trail in the future would be able to develop their own stories based on aspects that they may want to put more emphasis on (Appendix 7.3).

Fig. 7.3: Irchel Nature Trail map.

Fig. 7.4: Collaborators for Irchel Nature Trail building. Upper row, from left to right: Dr. Jobran Chabran, Dr. Mollie Chapman, Gwyneth Halstead-Nussloch, Dr. Reiko Akiyama; Lower row, from left to right: Vanessa Weber de Melo, Alizée Le Moigne, Dr. Frank Pennekamp, Sara Petchey (with Heath and Drew), Dr. Morana Mihaljević and Alejandra Parreño

Fig. 7.5: Example board with key elements. 1) *Title* (short, appealing), 2) *Main section* (as visual as possible, includes short texts, and uncommon topics – e.g., in this board the inclusion of moths as valuable biodiversity, and not only butterflies which people are more familiar with), 3) *Glossary section* (brief definition of complex terms used in the introduction or main text), 4) *Map of the trail* (designed to highlight the main points of interest in the campus and aid in location), 5) Social media (to encourage interaction), 6) *Quiz section* (questions with defined answer, or open, as it is in this case, to stimulate thinking and active learning – as opposed to passive), 7) *QR code (*link to more information and novel research produced at the university), 8) *Introduction* (short but with content, should invite audience to continue reading), 9) *Icon* (designed for easy identification of topics), 10) *Logo* (branding of the project as independent but part of the university of Zurich), 11) Topic image (clear image that represents the topic). Design: Designers' Club (private, external company), in collaboration with the Irchel Nature Trail Team.

Outcome: The trail was opened on the International Day of Biologic Diversity (22 May 2019) and it is set to last for at least 5 years. Over 100 people attended the opening day and every day hundreds of people cross the campus which potentially interact with it. Responses to the trail from the community have been in the majority positive, citing it as a nice activity to do with family and a source of information.

Irchel Clean-up Day

The Irchel Clean-up Day was a spin-off from the Irchel Nature Trail, particularly from the exploration done to obtain information and pictures for board number 1 (about litter). During this exploration, I collected trash during 1 hour from the Irchel Park, in September 2018, with the help of Cornelia Carnal, the IT manager of the department who volunteered. We found a significant amount of cigarette butts (near 400), plastic packaging and bottle caps outside of the correspondent trash cans. At the same time, we caught the attention of visitors of the park who got curious on what we were doing and how they could see the results of the search. This prompt us to develop an educational project to promote avoiding littering and teach about the consequences for nature and human health of litter in green urban spaces. We applied for funding from the Sustainability Committee and coordinated a team of 15 volunteer students, and 80 part-time volunteers from the community of Zurich to clean the park in August 2019 (9-16 hs). We received additional assistance from the management team of the university, in order to dispose the collected trash.

Trans-disciplinary collaboration with businesses, NGOs and the city

We contacted local business around the park that could be related with sustainability or sustainable projects (e.g., zero waste shops, bio-cafes, recycling companies, organic fruit dealers) and asked them if they would be willing to sponsor the Irchel Clean-up day with prizes for participants. We had a positive response; five businesses contributed to finance prizes, for a value of approximately CHF 1000 in total, and two NGOs supported the cause, from which one sent representatives to do outreach on site on the effects of litter in wild animals (see Fig 7.6 for logos at the bottom of the advertisement poster). A local entrepreneur supplied us with 80 portable ashtrays as give-aways, we had merchandizing from the University of Zurich and we purchased refreshments from a local, organic apples farmer. We collaborated with a master student from the University of Zurich, who was doing her thesis on the psychology of littering, and presented her thesis design and progress to the community. From the city of Zurich, we received a parliamentarian from the Canton of Zurich, who distinguished the effort of the community with a certificate of appreciation.

Fig 7.6: Poster for the Irchel Clean-up day. I based the structure and the design on the ones professionally done for the Irchel Nature Trail, with the aim of stablishing a branding for future efforts related to sustainability in the park.

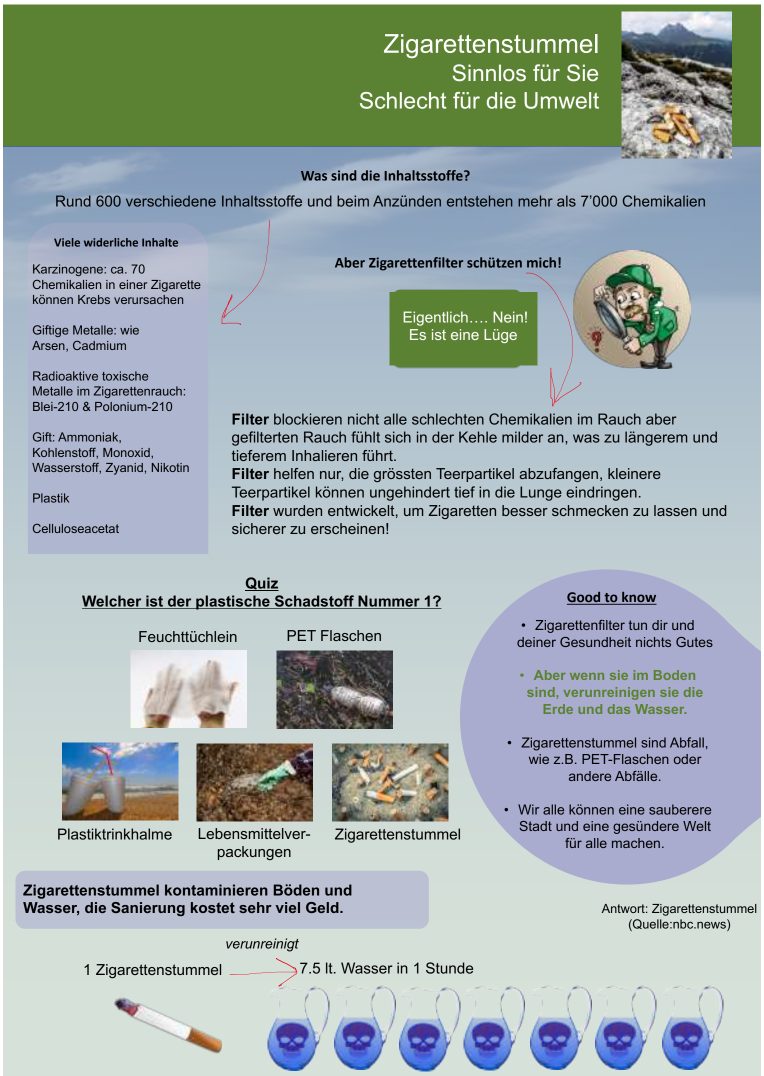


Fig 7.7: Poster on the effects of cigarette-butts in the environment and health. The design concept was to include visual elements that can quickly be interpreted by a general audience, in an interactive way (game).

Litter collection

Table 7.1 shows the amount per type of collected trash. The predominant trash, as expected, were cigarette butts. Although we originally planned to establish a map of the zones of the park with higher incidence of littering, it was not possible to do so because volunteers did not stay in delimitated areas, hence the collected trash could not be normalized by the effort per number of volunteers (to improve in future efforts). Most of the cigarettes, plastic and bottles were found near the most transited areas of the lower trail and lake, but a large amount of what seemed "old litter" (degraded) was stuck in less accessible areas (in between dense vegetation), probably spread by wind and animals.

Table 7.1: Litter collected at Irchel-Park (September 2019). Number of volunteers 80; average number of hours per person: 2 hs.

Item	Amount (in pieces)	Destination
Cigarette butts	3901	General waste
Plastic packaging	1523	General waste
Paper	1114	Recycled
Alu	729	Recycled
Metal	123	Recycled
Glass	607	Recycled
PET Bottles	72	Recycled
Lost items	50	General waste

Reception

We sent evaluation forms to all volunteers that signed up, from which we received 15 answers. Responses indicated that the event was valued by the community and considered timely. Constructive improvements were related to providing better services during the day, such as bathrooms and a cafeteria opened (given that it was done in a day when the university was closed). The community seemed engaged and enthusiastic and I recommend that this project would continue yearly (Fig. 7.8).

Fig. 7.8: Educational activities and litter recycling at the BML tent

Acknowledgements

Thank you, Morana and Sara, for being my source of inspiration to act and reach out! Thank you, Owen, for allowing the space and time within my thesis to pursue this passion. Thank you to everyone the community of Zurich for your active participation in all these projects and continuous support.

7.3 Appendix O (Outreach)

7.3.1 Science stories for Biodiversity Means Life project

a) Naturalness levels of the landscape

b) Biodiversity in land use changes

a) What is ecological naturalness in landscape?

Humans have been modifying nature for centuries. As a result, beautiful places that we might consider "natural", are actually the result of human interventions. Obvious examples of man-made landscapes can be a farm, a city or gardens. But sometimes it is hard to realize when something is natural or artificial: for example, when a forest is native, grown for forestry or part of a restoration program. Of course, there are different levels of intervention, from landscapes that have been completely designed and managed to those where only side effects of civilization have reached, usually called semi-natural. In fact, it is considered that no landscape has been left in its natural state, but all have different degrees of "naturalness", which is the way we perceive landscapes as being natural or man-made. Ecological naturalness, refers to the ecological aspects of our interventions in nature.

There is nothing inherently wrong with artificial landscapes; they provide humans with a home, food, recreation, and everything we need to survive. However, as a landscape becomes more artificial, usually the least it can preserve the biotic interactions, or keep resources clean in the long term. Therefore, it is certainly good to be able to identify them and not forget the goods that natural landscapes also represent for human wellbeing, biodiversity and ecosystem functions in general. Whenever possible, we should try to reduce our long-term impact in both, so as to allow for adaptation and preserve resources. Aborigine tribes in the past usually strived in achieving this, as they developed at the pace of natural processes, without major impacts in the environment.

So how to identify human footprints in the landscape? For instance, we humans tend to create geometric structures: squared gardens with uniform edges and symmetrically placed flowers, straight rivers without meanders or slopes, and uniform forests with little diversity of species. In order to build our farms and cities, we usually shift the course of rivers, the shape of lakes, the limits with the ocean (usually by filling wetlands with soil), we cut long grasses to keep them tidy and we bring water to deserted or cold areas to make them more productive. All the elements that we use for these activities denote a landscape that has been adapted to human needs. Lately, there are trends to preserve natural landscapes that represent the opposite to this traditional management but still constitute an intervention, for example green roofs in cities or letting native weeds grow in the borders of farms to protect local flora and fauna.

Preserving landscapes as close to native as possible is tricky, as we flood the world with foreign elements (like plastic) and we modify large scale processes (like climate or nutrient flow). However, we can still appreciate close to natural landscapes in national parks, reserves and not-habited places. Biodiversity is usually a reliable element of natural landscapes, although attention has to be paid to whether species are native or introduced and this requires a bit of historical knowledge on local ecosystems. Monitoring biodiversity in landscapes as an indicator of human impact is really important. Other hints of "naturalness" can be found in water, air and soil quality and in the periodicity of earth and climate processes, like volcano eruptions, floods from rivers rises, presence of all levels of food webs (from autotroph plants to top predators) and absence of non-biodegradable elements (like concrete or plastic). Eventually, when humans leave an area, nature takes back the wheel and drives ecosystems to a new state that in the distance future we could probably consider as "natural" again.

b) Happy Insects, Happy Farms - Is there a space for nature in agriculture?

Humanity has a large impact on Earth. Agriculture is one of the major drivers of negative impacts, second only to fossil fuels and mineral extraction. In some way, we could say society started with agriculture and still today is the backbone of our subsistence. The farm is a unique socio-ecological system; fishermen don't live in the middle of the sea, but farmers mostly live in their farms. In that way, many worlds coexist and collide in the farm: producers, consumers, farm or domestic animals, crop species, “weeds”, rodents, birds, water and nutrient cycles; the list is long. One of the main worlds in this system, are insects.

What are insects? Insects are small arthropods of 6 legs, 3 defined body parts and an external skeleton; the one that makes a characteristic “pop” when we step over one of them. But that is almost all that insects have in common. For the rest, the 900 thousand species of known insects, out of the between 2 and 30 million estimated to exist, are quite different.[1] This wonderful diversity, the largest of all animal groups, is what makes any species that comes to our mind, a poor example to generalize on the rest. Insects can pollinate or be vectors of diseases, they can be predators or prey, they can be parasites or symbionts, they can be disgusting or beautiful, they can be eaten or kill you. While their role might differ, they are all relevant for ecosystem functioning, directly or indirectly.

In the farm, we can group insects as beneficial or harmful, according to their direct impact on agriculture; these are insects of economic importance. ***Beneficial insects*** are mainly: 1) pollinators, that help plants reproduce, 2) predators and parasitoids, that help control pests, 3) scavengers and decomposers, that help to break down matter and 4) insects that produce economically valuable products, like honey or silk. ***Harmful insects*** **(pests)** are mainly: 1) herbivores, that eat crops, 2) insects with endo-parasitic larvae that develops inside fruits, and 3) disease vectors of plant, animal or human diseases.

Indirect effects of insects in the farm are mainly related to the functioning of the ecosystem that the farm is embedded in, usually grasslands. Seemingly “neutral” insects still have a relevant role through their participation in resources cycles and food webs that keep the ecosystem stable and productive. Many of them can even be used as bio-indicators of environmental quality ***.***

Are they indestructible? Insects are relatively small and reproduce in high rates compared to other animals. Therefore, we might be tempted to think of their populations as being sort of indestructible. As if their resilience would allow them to always recover from environmental damage or to always find a new space to resettle. The fact that there is often some redundancy in their roles (e.g.: many species pollinating one plant), can sometimes lead us to think that the non-natural extinction of a species will not be major in the overall ecosystem network.

This is far from true. Insect populations are highly sensible to changes in their environment. For example, small temperature increases can modify the developmental time of parasitoids. When timing mismatches occur between the development of parasitoids and their host, pest control efficiency is reduced.[2] Another example is the presence of insecticides aimed at reducing harmful insects like mosquitoes, that have shown a collateral effect on bumblebees even in low doses, hindering their colony growth.[3] Recent studies have raised concerns of an alarming insect population decline worldwide, even in protected areas. This is not only a threat for nature but also for economy: conservative figures put the economic value of native insects' work in the fields of the USA at $0.38 billion for dung burial, $3.07 billion for pollination and $4.49 billion for pest control.[4] Globally, this is of course a much larger figure.

What are the threats and what can I do about it? The main threats for insects in agriculture are loss of habitat, climate change and contamination through chemicals, like herbicides and pesticides. Habitats get lost when we eliminate the places where insects develop, reproduce and feed, like marshes, ponds, bushes and "weeds", so as to increase arable and grazing land, which goes into intensive constant management. Climate change is exacerbated by the destruction of carbon sinking sources (like forests), meat production and water contamination through runoff from the fields. Herbicides and pesticides kill adult insects or affect their development severely.

Addressing these three sources of damage can seem daunting. However, it all starts at home. Small changes add up to a better quality of life for insect populations and a healthier production system overall. Providing hedges in farms, synching mowing to insect developmental and reproduction times, synching pesticide application to daily insect rhythms to avoid their exposure, providing safe shelters for insects nearby farms, increasing landscape connectivity with corridors and urban ecology; these are feasible actions. Most importantly, acknowledging our impact and the existence of our little neighbors will help us make informed economic and political decisions. ***For instance, do you know where the different types of insects mentioned in this essay live?***

At times, it may seem that we don't have enough information to make decisions. It is true; there is much we don't know about the complex insect world. But this we know: it takes more time and money to repair a damaged ecosystem, than to prevent its damage. This should be enough to apply a precautionary principle and provide a space in agriculture for insects to be happy. Many worlds coexist and collide in the farm. A healthy farm in the long term will only be possible if the scale inclines more on coexistence, than collision.

Bibliography

1. Smithsonian. Numbers of Insects (Species and Individuals). at <https://www.si.edu/spotlight/buginfo/bugnos>;

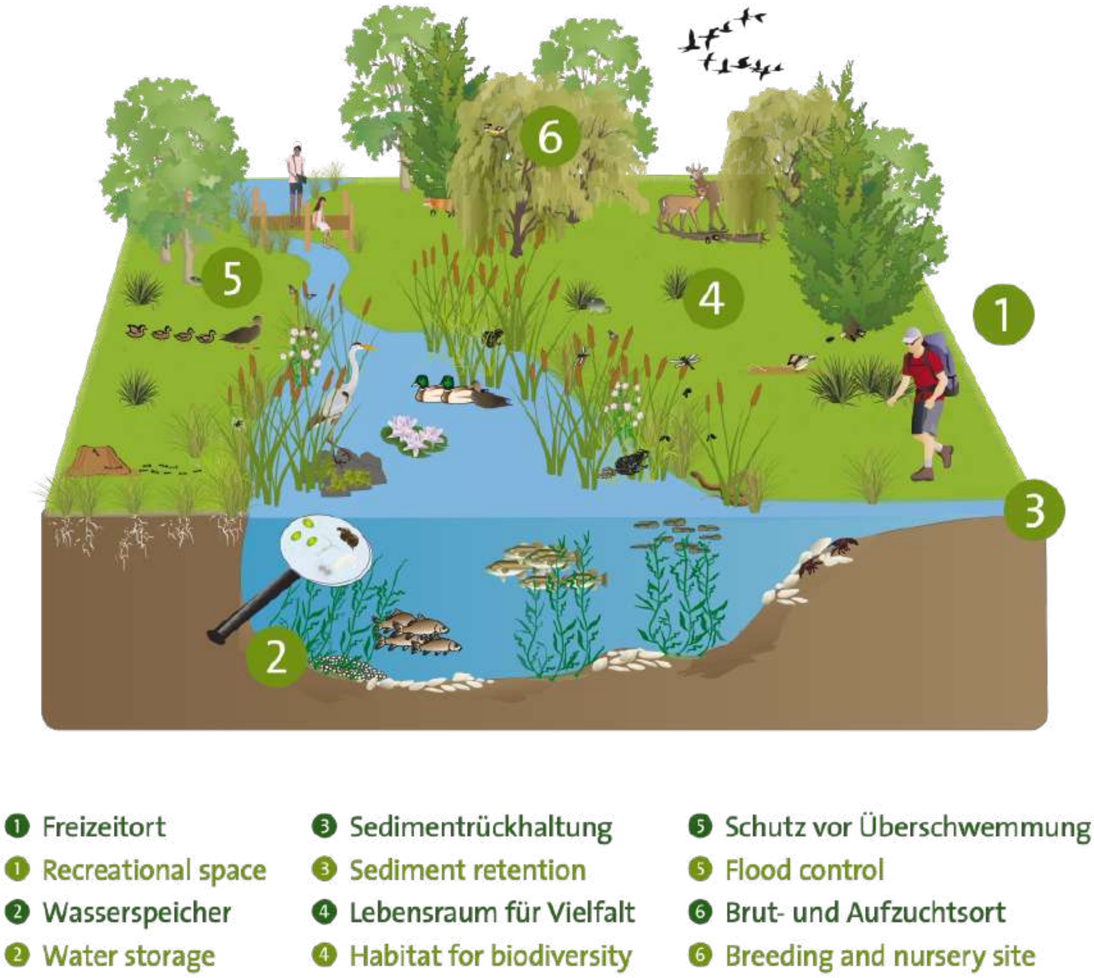
2. Jeffs, C.T. & Lewis, O. T. Effects of climate warming on host–parasitoid interactions. *Ecol. Entomol.* **38,** 209–218 (2013).

3. Whitehorn, P. R., O'Connor, S., Wackers, F. L. & Goulson, D. Neonicotinoid Pesticide Reduces Bumble Bee Colony Growth and Queen Production. *Science* (2012). doi:10.1126/science.1215025

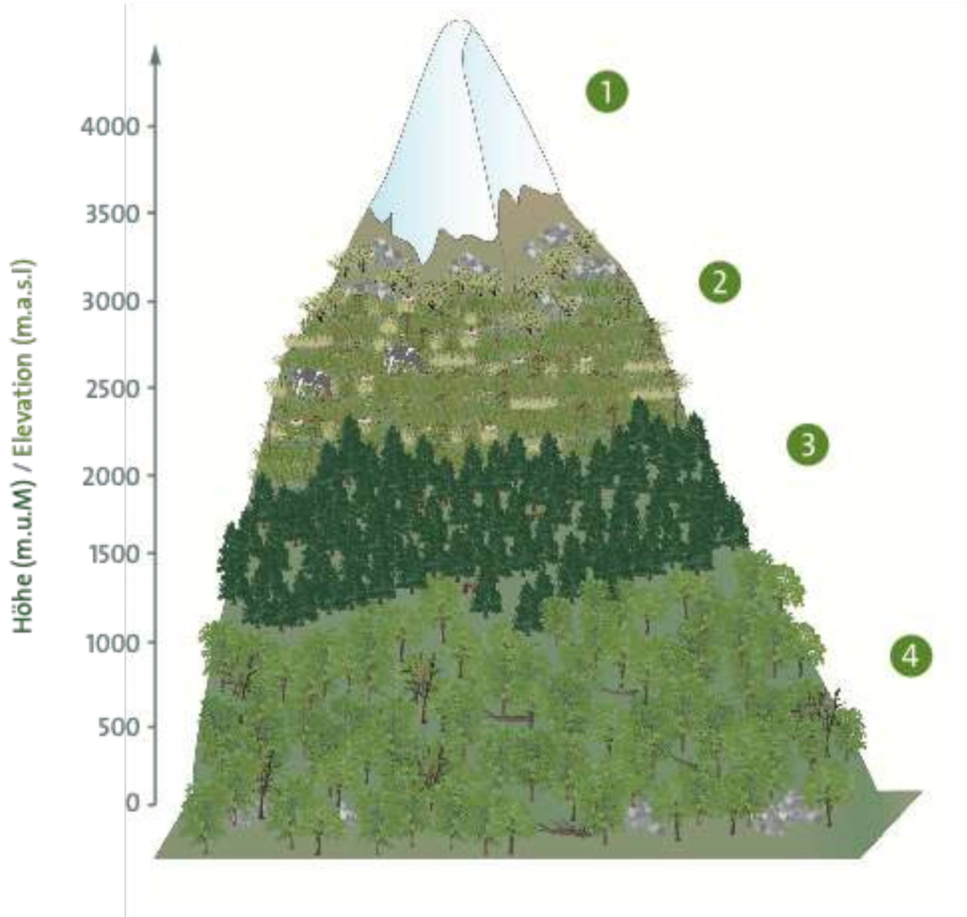
4. Losey, J. E. & Vaughan, M. The Economic Value of Ecological Services Provided by Insects. *BioScience* **56,** 311–323 (2006).

7.3.2 Schemes developed for the Irchel Nature Trail

a) **Wetlands: ecosystem services provided**

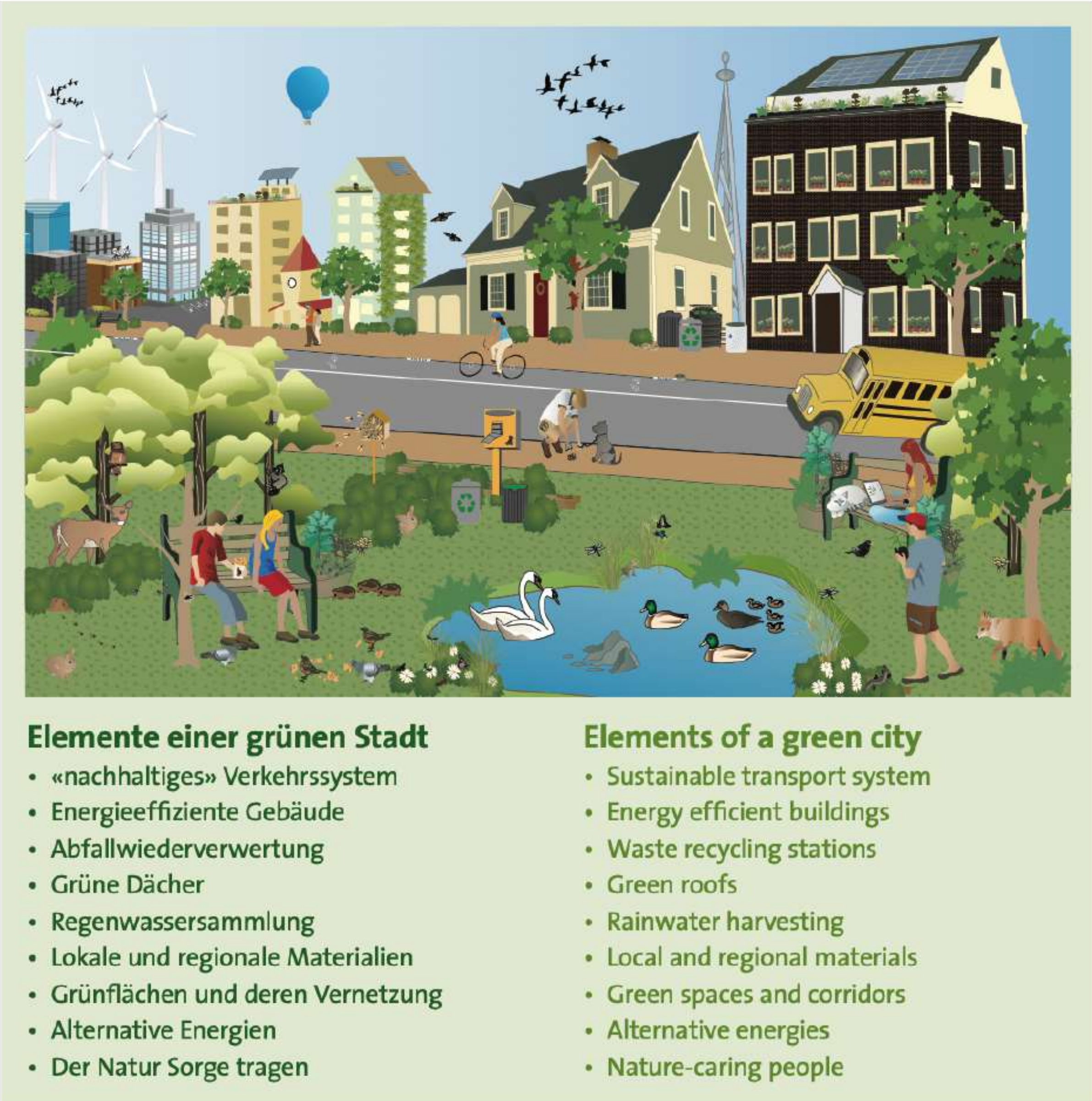


b) Mountain Ecology: Zonation of biodiversity due to altitude



1 Gletscherzone / Glacial zone
2 Alpiner Rasen (Wiese) / Alpine zone (Alpine meadeadows)
3 Subalpine Stufe 2 (Nadelwald) / Subalpine zone 2 (Coniferous forest)
4 Subalpine Stufe 1 (Laub- & Mischwald) / Subalpine zone 1 (Mixed deciduous forest)

c) Urban Ecology: Elements of a green city



8. General References

Agarie, M., Nagase, A., Ono, K., & Watanabe, M. (2015). *A Study of Insect Hotel Use as Environment Education in Japan*. *62*, 225. https://doi.org/10.11247/jssd.62.0_225

Barry, A., & Born, G. (2013). Interdisciplinarity: Reconfigurations of the social and natural sciences. In *Interdisciplinarity: Reconfigurations of the social and natural sciences* (pp. 1–56). Routledge.

Becker, C. D., & Ostrom, E. (1995). Human ecology and resource sustainability: The Importance of Institutional Diversity. *Annual Review of Ecology and Systematics*, *26*(1), 113–133. https://doi.org/10.1146/annurev.es.26.110195.000553

Bennett, E. M., Cramer, W., Begossi, A., Cundill, G., Díaz, S., Egoh, B. N., Geijzendorffer, I. R., Krug, C. B., Lavorel, S., Lazos, E., Lebel, L., Martín-López, B., Meyfroidt, P., Mooney, H. A., Nel, J. L., Pascual, U., Payet, K., Harguindeguy, N. P., Peterson, G. D., … Woodward, G. (2015). Linking biodiversity, ecosystem services, and human well-being: Three challenges for designing research for sustainability. *Open Issue*, *14*, 76–85. https://doi.org/10.1016/j.cosust.2015.03.007

Berti, P. R., Krasevec, J., & FitzGerald, S. (2004). A review of the effectiveness of agriculture interventions in improving nutrition outcomes. *Public Health Nutrition*, *7*(5), 599–609. Cambridge Core. https://doi.org/10.1079/PHN2003595

Biesbroek, R., Dupuis, J., & Wellstead, A. (2017). Explaining through causal mechanisms: Resilience and governance of social–ecological systems. *Sustainability Governance*, *28*, 64–70. https://doi.org/10.1016/j.cosust.2017.08.007

Black, M. (1946). *Critical thinking: An introduction to logic and scientific method* (Vol. 12). Prentice-Hall, Inc.

Bonney, R., Phillips, T. B., Ballard, H. L., & Enck, J. W. (2015). Can citizen science enhance public understanding of science? *Public Understanding of Science*, *25*(1), 2–16. https://doi.org/10.1177/0963662515607406

Boons, F. (2013). Organizing Within Dynamic Ecosystems: Conceptualizing Socio-Ecological Mechanisms. *Organization & Environment*, *26*(3), 281–297. https://doi.org/10.1177/1086026613498755

Bowman, D. M. J. S., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'Antonio, C. M., DeFries, R., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Mack, M., Moritz, M. A., Pyne, S., Roos, C. I., Scott, A. C., Sodhi, N. S., & Swetnam, T. W. (2011). The human dimension of fire regimes on Earth. *Journal of Biogeography*, *38*(12), 2223–2236. https://doi.org/10.1111/j.1365-2699.2011.02595.x

Bracken, L. J., Bulkeley, H. A., & Whitman, G. (2015). Transdisciplinary research: Understanding the stakeholder perspective. *Journal of Environmental Planning and Management*, *58*(7), 1291–1308. https://doi.org/10.1080/09640568.2014.921596

Brewer, C. (2006). Translating Data into Meaning: Education in Conservation Biology. *Conservation Biology*, *20*(3), 689–691. JSTOR.

Buijs, A. E. (2009). Lay People's Images of Nature: Comprehensive Frameworks of Values, Beliefs, and Value Orientations. *Society & Natural Resources*, *22*(5), 417–432. https://doi.org/10.1080/08941920801901335

Campos, C., Nates, J., & Lindemann-Matthies, P. (2013). *Perception of and knowledge about biodiversity by urban and rural students of central-west drylands of Argentina*. *23*(3), 174–183.

Carmenta, R., Parry, L., Blackburn, A., Vermeylen, S., & Barlow, J. (2011). *Understanding human-fire interactions in tropical forest regions: A case for interdisciplinary research across the natural and social sciences*. *16*(1), 53.

CBD. (2018). *Key messages from the workshop on "Biodiversity and Climate change: Integrated science for coherent policy."* Convention on Biological Diversity. https://www.cbd.int/doc/c/c429/2df7/dc8cc589bbf1f5b58f8a1d63/cop-14-inf-22-en.pdf

Cheung, M. W.-L. (2015). Meta-analytic structural equation modeling. In *Meta-Analysis* (pp. 214–278). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118957813.ch7

Cooper, H., & Hedges, L. V. (2009). Research synthesis as a scientific process. In *The Hand. Of Res. Synthesis and Meta-Analysis* (2nd ed., pp. 3–16). Russell Sage Foundation.

Cornell, S., Berkhout, F., Tuinstra, W., Tàbara, J. D., Jäger, J., Chabay, I., de Wit, B., Langlais, R., Mills, D., Moll, P., Otto, I. M., Petersen, A., Pohl, C., & van Kerkhoff, L. (2013). Opening up knowledge systems for better responses to global environmental change. *Special Issue: Responding to the Challenges of Our Unstable Earth (RESCUE)*, *28*, 60–70. https://doi.org/10.1016/j.envsci.2012.11.008

Costanza, R., Fisher, B., Mulder, K., Liu, S., & Christopher, T. (2007). Biodiversity and ecosystem services: A multi-scale empirical study of the relationship between species richness and net primary production. *Ecological Economics*, *61*(2–3), 478–491. https://doi.org/10.1016/j.ecolecon.2006.03.021

Cretney, R. (2014). Resilience for Whom? Emerging Critical Geographies of Socio-ecological Resilience. *Geography Compass*, *8*(9), 627–640. https://doi.org/10.1111/gec3.12154

Domoney, D. (2019). *Complete Guide to making your own insect hotel*. https://www.sustainablelearning.com/sites/default/files/asset-files/funky_bug_hotels_david_domoney.pdf

Dovers, S. R., Norton, T. W., & Handmer, J. W. (1996). Uncertainty, ecology, sustainability and policy. *Biodiversity & Conservation*, *5*(10), 1143–1167. https://doi.org/10.1007/BF00051569

Dube, O. P. (2009). Linking fire and climate: Interactions with land use, vegetation, and soil. *Current Opinion in Environmental Sustainability*, *1*(2), 161–169. https://doi.org/10.1016/j.cosust.2009.10.008

Fay, P. A., Prober, S. M., Harpole, W. S., Knops, J. M. H., Bakker, J. D., Borer, E. T., Lind, E. M., MacDougall, A. S., Seabloom, E. W., Wragg, P. D., Adler, P. B., Blumenthal, D. M., Buckley, Y. M., Chu, C., Cleland, E. E., Collins, S. L., Davies, K. F., Du, G., Feng, X., … Yang, L. H. (2015). Grassland productivity limited by multiple nutrients. *Nature Plants*, *1*, 15080.

Flick, U., von Kardorff, E., & Steinke, I. (2000). *A companion to qualitative research*. Sage Publications.

Flombaum, P., & Sala, O. E. (2008). Higher effect of plant species diversity on productivity in natural than artificial ecosystems. *Proceedings of the National Academy of Sciences*, *105*(16), 6087–6090. https://doi.org/10.1073/pnas.0704801105

Grace, J. B., Adler, P. B., Stanley Harpole, W., Borer, E. T., & Seabloom, E. W. (2014). Causal networks clarify productivity–richness interrelations, bivariate plots do not. *Functional Ecology*, *28*(4), 787–798. https://doi.org/10.1111/1365-2435.12269

Grace, J. B., & Pugesek, B. H. (1997). A Structural Equation Model of Plant Species Richness and Its Application to a Coastal Wetland. *The American Naturalist*, *149*(3), 436–460. https://doi.org/10.1086/285999

Gredler, G. (1999). *Sustainable Gardening: The Oregon-washington Master Gardener Handbook*. Oregon State University; EM 8742. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw550.pdf

Griffiths, M., & Voigt, F. (2014). Insect hotels—Adding beauty and diversity to our gardens. *Veld & Flora, 100*(4), 165–167.

Hackmann, H., Moser, S. C., & St. Clair, A. L. (2014). The social heart of global environmental change. *Nature Climate Change*, *4*(8), 653–655. https://doi.org/10.1038/nclimate2320

Haigh, N., & Griffiths, A. (2009). The natural environment as a primary stakeholder: The case of climate change. *Business Strategy and the Environment*, *18*(6), 347–359. https://doi.org/10.1002/bse.602

Harpole, W. S., Sullivan, L. L., Lind, E. M., Firn, J., Adler, P. B., Borer, E. T., Chase, J., Fay, P. A., Hautier, Y., Hillebrand, H., MacDougall, A. S., Seabloom, E. W., Williams, R., Bakker, J. D., Cadotte, M. W., Chaneton, E. J., Chu, C., Cleland, E. E., D'Antonio, C., … Wragg, P. D. (2016). Addition of multiple limiting resources reduces grassland diversity. *Nature*, *537*(7618), 93–96. Scopus. https://doi.org/10.1038/nature19324

IPBES. (2011). Resolution 65/162—Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). *Intergovernmental Platform on Biodiversity and Ecosystem Services*. http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/65/162

IPBES. (2019). *Media Release: Nature's dangerous decline "unprecedented"; species extinction rates accelerating*. United Nations. https://www.ipbes.net/news/Media-Release-Global-Assessment

James, P., Ashley, J., & Evans, A. (2000). Ecological Networks: Connecting environmental, economic and social systems? *Landscape Research*, *25*(3), 345–353. https://doi.org/10.1080/713684679

Jarrett, R. (2003). The Environment: Collateral Victim and Tool of War. *BioScience*, *53*(9), 880–882. https://doi.org/10.1641/0006-3568(2003)053[0880:TECVAT]2.0.CO;2

Javeline, D. (2014). The Most Important Topic Political Scientists Are Not Studying: Adapting to Climate Change. *Perspectives on Politics*, *12*(2), 420–434. Cambridge Core. https://doi.org/10.1017/S1537592714000784

Johnston, J. (2005). *Early explorations in science* (Second edition). Open University Press.

Kennedy, C. M., Oakleaf, J. R., Theobald, D. M., Baruch-Mordo, S., & Kiesecker, J. (2019). Managing the middle: A shift in conservation priorities based on the global human modification gradient. *Global Change Biology*, *25*(3), 811–826. https://doi.org/10.1111/gcb.14549

Koppe, E. V. (2014). *The Principle of Ambituity and the Prohibition against Excessive Collateral Damage to the Environment during Armed Conflict* (pp. 59–90). Brill | Nijhoff. https://doi.org/10.1163/9789004270657_005

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). *Handbook of meta-analysis in ecology and evolution*. Princeton University Press. https://doi.org/10.1515/9781400846184

Leinster, T., & Cobbold, C. A. (2011). Measuring diversity: The importance of species similarity. *Ecology*, *93*(3), 477–489. https://doi.org/10.1890/10-2402.1

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. *Nature*, *519*(7542), 171–180. https://doi.org/10.1038/nature14258

Lindemann-Matthies, P. (2017). Perception of plant species richness by people with different nationalities—An experimental study. *Landscape Research*, *42*(5), 482–497. https://doi.org/10.1080/01426397.2017.1305343

Lindemann-Matthies, P., Keller, D., Li, X., & Schmid, B. (2013). Attitudes toward forest diversity and forest ecosystem services—A cross-cultural comparison between China and Switzerland. *Journal of Plant Ecology*, *7*(1), 1–9. https://doi.org/10.1093/jpe/rtt015

Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., & Li, S. (2015). Systems integration for global sustainability. *Science*, *347*(6225). https://doi.org/10.1126/science.1258832

Magurran, A. (2004). *Measuring Biological Diversity*. Blackwell Publishing.

McKie, R. (2013). Children will suffer most as climate change increases in coming decades, say scientists. *BMJ : British Medical Journal*, *347*, f5799. https://doi.org/10.1136/bmj.f5799

MEA. (2005). *Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf

Mendelsohn, R., Dinar, A., & Williams, L. (2006). The distributional impact of climate change on rich and poor countries. *Environment and Development Economics*, *11*(2), 159–178. Cambridge Core. https://doi.org/10.1017/S1355770X05002755

Moon, K., Adams, V. M., Januchowski-Hartley, S. R., Polyakov, M., Mills, M., Biggs, D., Knight, A., Game, E. T., & Raymond, C. M. (2014). A Multidisciplinary Conceptualization of Conservation Opportunity. *Conservation Biology*, *28*(6), 1484–1496. https://doi.org/10.1111/cobi.12408

Oxford. (2019). Diversity. In *Lexico, by Oxford*. https://www.lexico.com/en/definition/diversity

Page, S. E. (2011). *Diversity and Complexity*. Princeton University Press.

Petrosillo, I., Zurlini, G., Grato, E., & Zaccarelli, N. (2006). Indicating fragility of socio-ecological tourism-based systems. *Theoretical Fundamentals of Consistent Applications in Environmental Management*, *6*(1), 104–113. https://doi.org/10.1016/j.ecolind.2005.08.008

Pullin, A., Frampton, G., Jongman, R., Kohl, C., Livoreil, B., Lux, A., Pataki, G., Petrokofsky, G., Podhora, A., Saarikoski, H., Santamaria, L., Schindler, S., Sousa-Pinto, I., Vandewalle, M., & Wittmer, H. (2016). Selecting appropriate methods of knowledge synthesis to inform biodiversity policy. *Biodiversity and Conservation*, *25*(7), 1285–1300. https://doi.org/10.1007/s10531-016-1131-9

Pullin, A., & Stewart, G. (2006). Guidelines for Systematic Review in Conservation and Environmental Management. *Conservation Biology*, *20*(6), 1647–1656. https://doi.org/10.1111/j.1523-1739.2006.00485.x

Reid, W. V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y. T., Mokhele, K., Ostrom, E., Raivio, K., Rockström, J., Schellnhuber, H. J., & Whyte, A. (2010). Earth System Science for Global Sustainability: Grand Challenges. *Science*, *330*(6006), 916. https://doi.org/10.1126/science.1196263

Roscher, C., Schumacher, J., Lipowsky, A., Gubsch, M., Weigelt, A., Pompe, S., Kolle, O., Buchmann, N., Schmid, B., & Schulze, E.-D. (2013). A functional trait-based approach to understand community assembly and diversity-productivity relationships over 7 years in experimental grasslands. *Perspectives in Plant*

Ecology Evolution and Systematics, *15*(3), 139–149. https://doi.org/10.1016/j.ppees.2013.02.004

Rudel, T. K. (2008). Meta-analyses of case studies: A method for studying regional and global environmental change. *Global Environmental Change*, *18*(1), 18–25. https://doi.org/10.1016/j.gloenvcha.2007.06.001

Spies, T. A., White, E. M., Kline, J. D., Fischer, A. P., Ager, A., Bailey, J., Bolte, J., Koch, J., Platt, E., Olsen, C. S., Jacobs, D., Shindler, B., Steen-Adams, M. M., & Hammer, R. (2014). Examining fire-prone forest landscapes as coupled human and natural systems. *Ecology and Society*, *19*(3). JSTOR. www.jstor.org/stable/26269597

Spock-Nimoy, L. (1973). The Infinite Vulcan. In *Star Trek*.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). https://doi.org/10.1126/science.1259855

Thesaurus. (2019). Turn Aside. In *Thesaurus*. https://www.thesaurus.com/browse/turn%20aside

Vacha, Z., & Petr, J. (2018). *Inquiry based education at primary schools through school gardens*. *11*(2).

Wood, P. (2003). *Diversity: The invention of a concept* (Encounter Books).

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"*Infinite diversity in infinite combinations…*

symbolizing the elements that create truth and beauty."

(Spock-Nimoy, 1973)

Integration of Global-Change Drivers and Biodiversity

Dissertation of doctoral studies in biology (ecology) from **María Alejandra Parreño** (PhD Candidate 2015-2020). Main supervisor: **Prof. Dr. Owen Petchey**.

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ALEJANDRA PARREÑO

Ecology I Sustainability

EDUCATION

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05/2020 – PhD Ecology
University of Zurich (UZH), Switzerland
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Relevant to: global change science, sustainability, agroecology, data synthesis

01/2015 – MSc Behavior, Evolution and Conservation
University of Lausanne / Eawag, Switzerland
Topic: Wing shape in aphid parasitoids: separating genetic variation from host-induced plasticity
Relevant to: biological control of pests, entomology, taxonomy, agroecology

11/2012 – BSc Ecology and Evolution
University of Buenos Aires / INTA - Conicet, Argentina
Topic: Study on the dynamics of genetic variability of a native fruit fly species during adaptation to laboratory rearing conditions.
Relevant to: biological control of pests, entomology, population genetics, agroecology

RESEARCH OUTPUT

- Parreño, MA., Petchey, S., Chapman, M., Altermatt, F. et al. (2020), Improving our understanding of biodiversity through everyday experiences, People and Nature (in revision)
- Parreño, MA., Schmid, B., Petchey, O. (2020), Identification, comparison, and analysis of hypotheses in systematic review (submitted)
- Liendo, MC., Parreño, MA., Pietrek, A., Bouvet, J., Milla, F., Vera, T., Cladera, J.,Segura, D. (2020), Infestation of fruit by conspecific and heterospecific females deters oviposition in two Tephritidae fruit fly species, J. Applied Entomol. (in review)
- Liendo, MC., Parreño, MA., Cladera, J., Vera, T., Segura, D. (2018), Coexistence between two fruit fly species is supported by the different strength of intra-and interspecific competition, Ecol. entomo. 43 (3), 294-303
- Emmenegger, R, Rowan, R., Zuppinger-Dingley, D., Krug, C., Parreño, MA., Korf, B. (2017), Ontology and integrative research on global environmental change: towards a critical GEC science, Curr. Opin. Env. Sust., 29, 131-137
- Parreño, MA., et al. (2016), Wing shape as a taxonomic trait: separating genetic variation from host-induced plasticity in aphid parasitoids, Zool. J. Linn. Soc., doi:10.1111/zoj.12490
- Scannapieco, A, Lanzavecchia, S., Parreño, MA., Liendo, MA., Cladera, J., Spivak, M. & Palacio, MA. (2016) Individual precocity, temporal persistence, and task-specialization of hygienic bees from selected colonies of *A. mellifera*, J. Apic. Sci., 60, 63–74
- Bush, A., Giménez, M., Grande, A., Morosi, L. G., Parasco, V., Parreño, M. A., et al. (2015), Synthetic crossfeeding cocultures in Yeast: computational model of autoregulation and design of a tryptophan export device, J. Synth. Biol., ID 178514
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Swiss National Science Foundation (2017)	CHF 22,000	Doctoral Mobility Grant
University of Lausanne (2015)	CHF 22,400	Master Grant by merit
Argentinian Department for the Environment (2011)	CHF 3,000	iGEM Grants for representation at MIT

ALEJANDRA PARREÑO

Ecology I Sustainability

SKILL-SET

	+ +++
Field and Semi-field work	
Programming (R Software)	
Data synthesis (metaanalysis, SEM)	
Bench work (genetics)	
Spatial analysis (GIS)	
Teaching	
Project management	
Event organization	
Scientific writing	
Design (Adobe family Software)	
Filmmaking (Short Documentaries)	

CONFERENCES (2019-2020)

	Presenter	Organizer
World Biodiversity Forum (Davos 2020)	X	X
British Ecological Society (Northern Irland 2019)	X	X
International Society for Conservation Biology (Malaysia 2019)	X	
URPP GCB Global Change and Biodiversity (Monte Verita 2019)	X	X

INTERESTS

REFERENCES

Prof. Dr. Owen Petchey
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Biology of Species Interactions Group
University of Zurich
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WORK EXPERIENCE

05/2020 - present — **Researcher**
Technical University of Munich, Germany
Design and test of flower stripes in agricultural landscapes on wild pollinators' health. Responsible for carrying field work and trans-diciplinary workshops.

04/2015 - 04/2020 — **Project manager**
URPP Global Change and Biodiversity, University of Zurich, CH
Integration of research projects on global change across a latitudinal gradient in six sites globally. Responsible for development of databases, editing of terminology and policy briefs, writing of opinion papers, construction of a nature trail and outreach projects.

06/2017 - 02/2018 — **Visiting Scholar**
Cardinale Lab, University of Michigan, USA
Data synthesis on plant community composition and productivity, shaped by competition for resources (nutrients, light). Responsible for data search and management, statistical analyses and communication of results.

02/2014 - 01/2015 — **Visiting Scholar**
Aquatic Ecology Group, Swiss Federal Institute of Aquatic Science and Technology, CH
Study on evolutionary biology of the parasitoid wasp species complex and host induced plasticity (aphids). Responsible for setting up and maintenance of colonies, analysis of geometric morphometrics, genetics lab techniques (PCR, DNA seq, cloning).

09/2013 - 01/2015 — **Research assistant**
Evolution & Mechanisms of Life History and Aging Group, University of Lausanne, CH
Study of mechanisms underlying the evolution of life history traits. Test of a candidate gene for aging using oxidative stress, molecular biology, experimentation, data analysis. Technical support in maintenance of *Drosophila sp.* laboratory lines.

02/2014 - 12/2014 — **Research assistant**
Behavior of Social Insects Group, University of Lausanne, CH
Study on insect behavior, ecology and chemical biology of *A. mellifera*. Technical support in projects, bench work, maintenance of beehives and field work.

01/2009 - 04/2014 — **Research assistant and Trainee**
Laboratory of Insects of Economic Importance, INTA (Argentina)
Study on the biology of insects of importance for agriculture (fruit flies, parasitoids, bees). Technical support in the molecular laboratory, field and semi-field experiments and mass rearing facilities. Responsible of improving procedures for genetic conservation of lab lines for Sterile Insect Technique control programs.

TEACHING (higher education) AND OUTREACH

- 2019 Introduction to meta-analysis for doctoral students (UZH)
- 2018 - 2019 Biodiversity Means Life outreach project - Volunteer organizer (UZH)
- 2017 Lecturer at Global Change and Biodiversity - Policy and Natural Economy (MOOC UZH - Coursera)
- 2016 - 2017 Teaching assistant Animal Behavior (UZH)
- 2015 - 2016 Teaching assistant Molecular and classic genetics (UZH)
- 2016 Teaching assistant Ecology (UZH)

INSTITUTIONAL RESPONSABILITIES

- Expert scientific member of the International Union for the Conservation of Nature, in the Commission for Ecosystem Management and Commission for Environmental, Economic and Social Policy.
- Member of the Steering Committee of the University Research Priority Program Global Change and Biodiversity (PhD and postdoc representative)
- Member of the Sustainability Committee of the Faculty of Science (UZH) and of the Sustainability Commission of the University of Zurich
- UZH scientific staff representative at the Commission for interdisciplinarity (UZH) and at the ActionUni national program for higher education